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RICHARD I. DICK

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DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF ILLINOIS
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FEBRUARY, 1971

MECHANISMS OF SLUDGE THICKENING

by

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Professor of Civil Engineering
University of Illinois

FINAL PROJECT REPORT

A Summary of Research Conducted
under Research Grant 17070 DJR from
the Federal Water Quality Administration
Environmental Protection Agency

Urbana, Illinois
February, 1971

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ABSTRACT

Two areas were emphasized in this research on gravity thickening of sludges. One was investigation of fundamental thickening properties of sludges. The other was consideration of rational criteria for thickener design and operation consistent with the observed fundamental thickening properties. Most results have been presented in detail in the professional literature and they are summarized and interrelated in this report.

The batch flux curve method of thickener analysis using settling data obtained with alternative sludge depths is considered to be the most reasonable method of thickener analysis available at present. The approach is based on experimentally determined sludge settling properties, and permits convenient evaluation of alternative design or operating conditions. Extreme care is necessary in measuring settling properties for gross anomalies in physical behavior can be created by laboratory test conditions. The maximum concentration which a sludge can reach by gravity thickening is a function of its compressive strength. Compressive strength, and hence the difficulty of thickening, increases exponentially with concentration. Permeability of the sludge bed controls both the rate of escape of clarified water and the portion of the effective weight of sludge solids which are effective in compressing underlying layers.

Also described in the report are results of work concerning the significance of sludge volume index measurements, the effect of possible methods of altering sludge settleability, the relationship between thickening and sludge rheology, the influence of biological variables on the rheology of activated sludge, the changes which occur in activated sludge aggregates during thickening, the *in situ* measurement of suspended solids, the application of the method of thickener analysis to full scale thickeners, and

the implications of the work to design of the activated sludge processes.

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I. INTRODUCTION

Importance of Thickening in Wastewater Management

In most waste treatment processes pollutants are concentrated by physical, chemical, or biological means into a settleable form for removal from the liquid waste stream. The solids might, for example, be chemical precipitants formed by reaction with ions in the waste stream, carbonaceous material concentrated in the form of microbial mass (in the case of biological waste treatment processes), or material contained in the suspended form in the raw waste.

Effective waste management requires effective treatment, handling, and disposal of the suspension of solids. The efficiency of virtually all methods of sludge treatment, handling, and disposal depends on the concentration of solids in the sludge. For example, the cost of transporting sludges depends almost directly on the dilution factor of the solids (AWTR, 1968) as does the required volume of sludge digesters (Shindala et al., 1970). The performance of sludge dewatering processes such as vacuum filtration and centrifugation also depends upon the degree to which solids can be concentrated in the feed (Sleeth, 1970). Clearly the economy of sludge combustion depends on achieving a high solids concentration so that the process becomes thermally self-sustaining (Hurwitz and Katz, 1959).

The most economical way of obtaining large sludge volume reductions is by gravity thickening. Depending on the nature of the sludge, one to tenfold volume reduction might be readily achieved by gravity thickening using reasonably simple and low-cost equipment. It normally is much more expensive to achieve similar volume reductions by mechanical means. The importance of thickening and waste management may be appreciated by considering that about 25 to 50 percent of the total cost of waste management is attributable to

sludge treatment handling and disposal (Levin, 1968).

In addition to the importance of gravity thickeners in sludge management schemes, thickening principles are also involved in many waste treatment processes. For example, any sedimentation tank is expected to accomplish a degree of thickening, and failure to consider this requirement in designing the facility can lead to unsatisfactory performance. Also, the performance of many related processes depends upon how well thickening is accomplished in sedimentation tanks. To illustrate, the size of the aeration tank in the activated sludge process depends upon how concentrated the microorganisms are in the sludge returned from the final settling tank. Similarly, the performance of flocculators in water and waste treatment processes depends upon the number of particle collisions which can be caused to occur and under given conditions, this is related to the concentration of particles present.

The problem and cost of sludge treatment may be expected to become more significant in the future as higher degrees of treatment result in production of large volumes of flocculent suspensions. In summarizing the importance of thickening research, Vinton Bacon (1966) has written: "Sludge concentration is the largest unsolved research and development problem. The savings that could be effected in this area alone would go a long way in improving other treatment processes and the effluent."

Purpose of the Project

In spite of the importance of gravity thickening and the frequency with which the process is used, little is known about how to design a thickener on the basis of a rational interpretation of the thickening phenomena. Most of the research which has been done on the process has been descriptive in nature and conventional design procedures which have evolved are often based on consideration of parameters such as surface loading which do not

necessarily have an influence on the performance of a gravity thickener.

The purpose of this work was to investigate the basic nature of the thickening process in order to afford an understanding of the performance of the process and to devise techniques for reliable design of thickeners on the basis of the fundamental properties of suspensions.

Project Organization

The work was supported by Federal Water Quality Administration Research Grant 17070 DJR from September 1, 1966 through August 31, 1969. Research in progress at the end of the grant period continued with support from the University of Illinois. The work was conducted at the Department of Civil Engineering, University of Illinois, Urbana, Illinois, under the direction of Richard I. Dick, Professor of Civil Engineering.

Much of the research was carried out by candidates for the Master of Science degree in sanitary engineering. The following graduate students were employed as research assistants on the projects:

T. R. Wallin	September 1966 - February 1967
A. R. Javaheri	September 1966 - August 1969
S. K Chakrabarti	February 1967 - May 1968
W. R. Gain	February 1968 - August 1969

Other graduate students conducted research related to the project in partial fulfillment of master's degree requirement but were not employed with project funds. These students, listed below, derived support from the project in terms of supplies and equipment but received their personal financial support from the training grant program of the Federal Water Quality Administration or the U.S. Public Health Service:

G. A. Farnsworth	September 1966 - February 1967
J. R. Quin	June - August 1967

J. I. Barkman February 1969 - August 1969

Mr. Barkman also received a supply and travel allowance from the Decatur, Illinois Water Company.

Other special studies for which the project provided supplies but not salaries included graduate projects by M. C. Babb and R. C. T. Wang, and undergraduate projects by J. C. Gratteau, W. R. Gain, and G. L. Caban. Miss Caban's work also received support from the National Science Foundation.

Others associated with the project included part-time laboratory technicians and Dr. B. S. Narang who was employed as a part-time Research Associate during the summer of 1968. Faculty members from various departments at the University of Illinois, especially Dr. B. B. Ewing of the Department of Civil Engineering, served gratuitously as project consultants.

Nature of this Report

Most of the major accomplishments of the project have been reported in the published literature, or were in preliminary manuscript form at the time this project report was prepared. Many of these papers and manuscripts are included in the appendices. The purpose of this report is to interrelate and summarize these individual publications, but not to repeat in detail work which previously has been described.

To distinguish between project publications and other publications, the reference list at the end of the report is divided into two sections. In the text, numbers preceded by "PR" are used to refer to references from the project publication list, while the author-year system is used to cite nonproject publications. Of the 31 project reports and publications listed, 18 have appeared in the published literature, of which five are included here as appendices.

Preparation of this report was delayed to permit inclusion of results of

work in progress at the end of the grant period. The research continued with support from the University of Illinois Civil Engineering Department and, later, from the Water Resources Center at the University of Illinois. Much of the work has been completed. However, results bred new ideas, and research is still in progress. Some of the continuing work makes use of equipment and concepts generated by the grant. Under these circumstances. judgments as to which accomplishments deserve inclusion in the final project report become somewhat arbitrary. In general, results of work which was underway at the end of the project period concerning excess hydrostatic pressure in subsiding sludge masses have been included here while those related to analysis of the performance of continuous thickeners have been excluded.

Because the focus of the research was on interpretation of thickening of sludges on the basis of observed basic physical characteristics and the relation of this fundamental behavior to the design of field scale thickeners, most of the work logically fell within one of two general categories. One category involved study of the basic physical properties of sludges which control its thickening behavior and the other category concerned work where the emphasis was on design of thickeners.

Research concerned principally with study of the physical characteristics of suspensions is described here in Chapter II entitled "Thickening Properties of Sludges." This chapter also includes studies related to the interpretation of results of laboratory batch sedimentation tests and some methodology associated with developments of the research work. Work which was related more directly to the design of full scale thickeners based on known sedimentation characteristics is included in Chapter III entitled "Thickener Design."

II. THICKENING PROPERTIES OF SLUDGES

Introduction

In order to consider rational design and operation of thickeners, it is necessary to be able to measure the physical properties of suspensions which influence their thickening behavior and to understand factors which control the physical properties of the sludge. In addition to providing insight into factors controlling the design and operation of gravity thickeners, knowledge of the interrelationship between physical properties and thickening behavior might permit alteration of the basic properties of suspensions by physical, chemical, or biological methods to improve the amenability of the sludge to thickening by gravitational means. Work related to study of the basic nature of the sludges and to experimental procedures required in evaluating sludge properties are reviewed in this chapter.

Measurement of Settleability

The property of a sludge most closely identified with its behavior in full-scale thickeners is its subsidence velocity under the influence of gravity. The apparent settling velocity of a particular concentration of sludge can be measured readily be observing the rate of subsidence of the liquid-solid interface following uniform dispersion in a transparent laboratory settling column. The test is deceptively simple, for serious errors can result because of conditions imposed by the laboratory test procedure.

Studies on the influence of laboratory test conditions on observed settleability were conducted as a part of this work, and were extended by cooperation with a related research program at the University of North Carolina. Principal factors found to affect results of laboratory sedimentation tests were the method for initially dispersing sludge solids, column diameter, sludge depth, and the presence or absence of slow speed stirring.

The extent to which these factors influence settling rate is highly dependent on the nature and concentration of the particular sludge solids.

Results of the work have been reported in detail in two publications (PR 10 and PR 29) and have been summarized in two others (PR 11 and PR 17). In general, with activated sludge, column diameter should be as large as possible and preferably not less than about 3 in., sludge depth should be comparable to the effective depth of the full scale facility, and slow stirring (with about 10 in./min tip speed) is essential. The greatest need for additional work in this area is for study of the relationship between the batch settling rate in cylinders to the settling rate of the same concentration of sludge under conditions which exist in a full-scale continuous thickener.

Realization of the great anomolies in settling behavior which could be caused by improper laboratory test conditions led to a critical evaluation of the test most commonly used to express the settleability and physical condition of sludge - the sludge volume index. These results also have been published (PR 18) and are included here as Appendix I. Basically, it was reported that the significance of sludge volume index values is seriously restricted by the nature of laboratory tests. While the test may have value as a plant operational tool, comparison of sludge volume index measurements from various plants is not meaningful. The test was considered to be wholly inadequate for research purposes, and alternative means for measuring the settleability and physical nature of sludge solids were suggested.

The experimental program involved with evaluating laboratory settling tests required a large number of suspended solids determinations. In order to select a convenient, reliable, and economical technique and to permit evaluation of the number of duplicate samples required to establish a desired

degree of precision, a study of alternative methods of determining the suspended solids concentration of activated sludge was conducted. Results, which have been published (PR 22) show, as a function of sample size and concentration, the coefficient of variation for four different methods of determining suspended solids. For the purpose of this study, the glass fiber filter Gooch crucible method with individual desiccators was considered to be superior.

Enhancement of Settleability

Studies of the alteration of settling behavior of sludges were undertaken for two reasons. One reason was to consider the practicality of altering the physical properties of sludges in full-scale applications. The other was to study the mechanisms responsible for the improved sedimentation in order to gain insight into the basic factors controlling sludge thickening.

The most fruitful of the studies of this type was an evaluation of the influence of polyelectrolytes on the settling behavior of activated sludge. The practicality of this technique in full-scale installations under certain circumstances was, of course, known from the published literature (for example, Jordan and Scherer, 1970) and the thrust of the study was to evaluate the basic change in the physical properties of activated sludge responsible for the improved settleability.

The major portion of the work was the subject of a master's thesis by G. A. Farnsworth (PR 20). Detailed results have been summarized in the form of a draft of a manuscript for publication (PR 21) which is included here as Appendix II. Settling properties were expressed as the ultimate settling velocity (the velocity at which the sludge would settle if it behaved as an ideal suspension (see Dick and Ewing, 1967b) and the retardation factor (a measure of the extent of deviation from an ideal suspension). Polymers were

found to influence primarily the ultimate settling velocity and did not appreciably alter the effect of interparticle contacts (as measured by the retardation factor). Because of this, the apparent effect of polymer addition may be highly dependent on the sludge depth used in laboratory experiments.

A preliminary evaluation of the feasibility of increasing activated sludge settling rates by imposing an electrical gradient was made (PR 23). While some slight effect could be shown the technique was not considered to be promising either for full-scale application or for more basic laboratory experimentation, and the work was terminated.

More extensive study was made of the effect of ultrasonic vibrations on the settleability of activated sludge (PR 30). The beneficial effect of ultrasonic vibrations on sludge settleability is well known, although the economic feasibility in full-scale applications remains dubious. The interest in this work was in learning more about basic settling characteristics of sludges by inquiring as to why exposure to ultrasonic vibrations improved settleability.

It was proposed that the basic mechanism explaining the improved thickening characteristics was removal of bound water by ultrasonic vibrations and then to measure its settling velocity and bound water content (using a modification of the technique described by Heukelekian and Weisburg, 1956). Significant reductions in bound water content and appreciable improvement in interface subsidence rate could be shown to be effected by exposure to ultrasonic vibrations prior to sedimentation. However, results were less well ordered than desired and quantitative evaluation was difficult. This experimental approach is still considered potentially fruitful, but improvements must first be made in the method for determining bound water content.

Thickening Mechanisms

Ultimately, it is desirable that rational approach to design and operation of gravity thickeners be founded on a basic understanding of the fundamental mechanisms involved in thickening. Previous work showed that the thickening behavior of activated sludge differed appreciably from that of the ideal suspension considered in basic thickening theory. Work described here was undertaken to explore causes of this difference and to evaluate changes which occur during the course of sludge thickening.

In work summarized in proceedings of the 4th International Conference on Water Pollution Research (PR 14 reproduced as Appendix III), a conceptual model of activated sludge thickening was developed. The model was based on mathematical analysis of the fluid and interparticle forces acting on a subsiding mass of sludge. Model predictions deviated from behavior of an ideal suspension, but agreed closely with the observed settling behavior of activated sludge. The relative magnitude of interparticle forces as computed from laboratory settling data using the model was related to the yield strength of the sludge as experimentally determined with a viscometer. This tended to confirm that the cause of deviation from the description of thickening offered by Kynch (1952) is the existence in activated sludge of interparticle forces.

Further examination of data previously reported (Dick and Ewing, 1967b) led to approximation of the concentrations at which interparticle forces begin to cause activated sludge sedimentation to differ from that of ideal suspensions (PR 10). As anticipated the concentration at which a continuous structure occurred was highly dependent on the nature of the sludge, but in each of the three plants studied the concentration was exceeded by the mixed liquor suspended solids concentration, and in one case it was as low as 650 mg/l.

In considering basic mechanisms of thickening, it is of interest to know whether water eliminated from sludge during thickening originates predominately from within flocculent masses of sludge solids or from the interstitial spaces between sludge aggregates. To answer this and related questions, activated sludge settling data were analyzed by use of two mathematical models (PR 25). One model (the Richardson-Zaki equation) related the settling velocity of a mass of particles to the discrete settling velocity of an individual particle comprising the mass, and the second (the Carmen-Kozeny equation) related flow through a porous bed to the physical properties of the bed. Similar conclusions were reached with both models. Results of the work were reported at an annual meeting of the Water Pollution Control Federation, and the complete published findings (PR 26) are included as Appendix IV.

Briefly, it was found that for activated sludges with good settling properties, thickening occurs primarily by elimination of interstitial water. However, with poorly settling sludges, much of the water removal in the course of thickening comes from inside the aggregates. The fraction of clarified liquid which originated from within aggregates increased as thickening took place. During thickening the aggregates which comprise the sludge are "squeezed" to eliminate water and "split" into smaller, more numerous, and more dense particles. To give some idea of the magnitude of values involved, in thickening a good activated sludge from about 0.5 percent solids to about 2.0 percent solids, the effective diameter of sludge solids decreased from 3 mm to 0.5 mm and the number of particles increased 30-fold. The ratio of the volume of floc particles to the volume of solids in the particles decreased from 57 to 72 and floc density increased from 1.0015 to 1.0032. At first, less than 10 percent of the water being eliminated from the sludge came from inside the aggregates, but at the end, more than 30 percent was

from this source.

A limitation of the work concerning aggregate changes during activated sludge thickening arose from the fact that when performing the calculations, allowance could not be made for the effect of structural support due to interparticle contracts. Experimentally, the amount of interparticle support in a subsiding suspension can be measured by observing the difference between the effective weight of solids above a point and the excess hydrostatic pressure at the point. However, this approach could not be used successfully with activated sludge because the extremely light weight of the sludge solids precluded accurate determination of excess hydrostatic pressure profiles. In work with a denser sludge - that from a water softening plant - it was found that allowance for interparticle support could readily be made by measuring concentration and excess hydrostatic pressure profiles. Preliminary work of this type (PR 27) was extended and is to be summarized in PR 28. A discussion of the experimental technique and a presentation of some of the pertinent results of this work is included as Appendix V.

The experimental approach afforded considerable insight into the basic mechanisms of thickening. The final solids concentration of a flocculent sludge depends on its compressibility and can be increased by increasing the weight of solids per unit area. The compressive strength of sludge was found to vary exponentially with solids concentration. Hence, it becomes exceedingly difficult to reach higher solids concentrations by gravity thickening. During the course of thickening the amount of the total weight of sludge which serves to compress underlying layers is a function of the permeability of the sludge. Thus, sludge with low permeability not only retards egress of clarified water, but also reduces the compressive force available to accomplish sludge consolidation. Stirring on sludge thickening in laboratory

vessels has been shown to increase compressibility and to reduce permeability.

The work on the basic nature of aggregate particles and their behavior in concentrated suspensions provided the basis for several contributions to the literature concerning the related work of others. In a discussion of Mueller, Voelkel and Boyle's work (1966) on activated sludge floc diameter (PR 5), the possibility for change of the size and water content of floc exposed to a shear field was discussed. Mechanisms of floc breakdown, sedimentation in laboratory vessels, and characterization of floc properties were considered in discussion (PR 12) of work by Ham and Christman (1969). Application of the Richardson-Zaki equation to activated sludge solids as described by Edeline, Tesarik, and Vostreil (1970) was discussed at the 4th International Conference on Water Pollution Research (PR 14). The effect of temperature on the rate of escape of water from subsiding sludge masses and on compressibility of sludge solids was considered (PR 13) in discussion of work by Reed and Murphy (1969).

Sludge Rheology

Advances in fundamental understanding of sludge thickening have been handicapped by lack of fundamental measures of the physical properties of sludges. As discussed in previous pages, the measure most commonly used, the sludge volume index, suffers from being influenced by many different physical characteristics of sludges, and it also reflects the nature of laboratory test conditions. Use was made in these studies of directly observable physical properties such as gravimetric concentration, settling velocity, and specific gravity and of calculated or estimated properties such as volumetric concentration, aggregate size, aggregate density, porosity, and permeability. However, none of these parameters gave a measure of the basic deformation and flow characteristics of sludge. Rheological measurements

were undertaken for this purpose.

It had previously been proposed (Dick and Ewing, 1967a) that basic rheological measures should prove useful in study of sludge treatment processes, and a viscometer suitable for measuring the rheological characteristics of activated sludge was described. For purposes of the work described in this report, the viscometer was improved. The modified version of the instrument, as described by Wang (PR 31) retained the basic features of the former instrument including outer cylinder rotation, roughening of cylinder surfaces, and use of a wide annular space between cylinders. Improvements incorporated in the modified version included oil damping of inner cylinder oscillation, use of calibrated torsion wires for measuring torque, and improved concentricity of the two cylinders. While the modified viscometer represents a vast improvement over the original version, additional improvements in range and convenience are desirable.

As discussed on previous pages, it was shown early in the project period (PR 14 reproduced as Appendix III) that reported deviations in the settling behavior of activated sludge from Kynch's theory could be interpreted in terms of the rheological behavior of the sludge. This was done by using a mathematical model of thickening to compute the relative magnitude of interparticle forces. This value, deduced by use of observed sedimentation data, was shown to be related to the yield strength of the sludge as measured in a viscometer.

Later in the project period, development of the procedure for measuring the absolute values of fluid resistance and interparticle resistance in dense sludges permitted a more direct comparison of settling behavior and rheological properties (PR 28 - see Appendix V). The compressive stress at which failure of sludge took place under the confined conditions of laboratory

batch sedimentation tests was related to the yield strength of the sludge.

In related studies of flotation thickening of activated sludge (Wood, 1970) the viscometer was used to measure the rheology of sludges being floated. Wood concluded that yield strength and plastic viscosity were the best parameters for characterizing sludges and for predicting flotation behavior.

Because activated sludge presents severe thickening problems, because its thickening performance had been shown to be related to its rheological characteristics, and because rheological characteristics were known to be influenced by the nature of the waste treatment plant (Dick and Ewing, 1967a), studies were undertaken (PR 2 and PR 3) to investigate how biological variables influenced sludge rheology. Results have been summarized in a prepublication manuscript (PR 19) which is included as Appendix VI.

The yield strength of a particular sludge was shown to be related to solids concentration and organic loading, while plastic viscosity was influenced principally by concentration only. Great reduction in yield strength was produced by aerobic digestion, and dramatic increases occurred shortly after feeding. However, with a constant organic loading and suspended solids concentration, changes in biological population could cause pronounced changes in both yield strength and plastic viscosity. Such changes were not necessarily accompanied by changes in performance of the biological phase of the activated sludge process. In the related studies by Wood (1970) it was confirmed that changes in sludge rheology under seemingly constant biological conditions were attributable to changes in morphological characteristics of the organisms making up the sludge. Such changes, which significantly affect sludge thickening properties are not reflected in a sensitive or definable way by the conventional sludge volume index.

III. THICKENER DESIGN

Introduction

An important aim, indeed the ultimate goal, of the research was to develop procedures for design and operation of gravity thickeners on a rational basis founded on knowledge of the fundamental thickening properties of suspensions. The bridge between thickening theory and practice is a long hazardous one resting on unsure abutments. For the body of knowledge on the basic thickening properties of suspensions is not large and most approaches to thickener design have not been rational.

However, the laboratory studies on basic settling properties afforded a basis for accepting or rejecting possible design approaches on a rational basis and study of data in the literature and analysis of the performance of full-scale thickeners gave additional basis on which to proceed. The work led to a proposed design technique applicable to the flocculent sludges encountered in sanitary engineering practice which not only permits rational approach to design, but also provides a framework for making the judgments required in thickener operation. Results of most of the work have been published (PR 7, PR 8, PR 9, PR 11, and PR 17) and are summarized in this chapter.

Analysis of Possible Approaches

A large number of approaches to thickener design and operation proposed by other workers were considered. Some of these could be rejected without detailed study whereas others were given careful analysis in order to develop a suitable framework for a model for thickener designs and operation.

Among those approaches which could readily be rejected were the common techniques based on hydraulic loading and sludge volume index. While hydraulic loading is a common basis for thickener design (Great Lakes - Upper Mississippi

River Board of Sanitary Engineers, 1960), it is only related to solids loading and is in itself wholly inadequate. The sludge volume index has often been advocated as a means for predicting thickener performance - particularly for the final settling tank in the activated sludge process (for example, Stewart, 1964). However, the work on the nature of the SVI test (PR 18) showed that the test would be very unreliable for this purpose.

Another common design approach is based on somewhat arbitrary establishment of retention time and solids loading (American Society of Civil Engineers, 1959). This approach is based on parameters which are more closely related to thickener performance, but the method does not permit the designer or operator of thickeners to weigh the consequences of alternative decisions.

Other approaches evaluated included empirical correlations of various variables with thickener performance. One such approach, by Pflanz (1970) involved the use of "solids feed" which was defined as surface settling rate times the feed solids concentration. In discussion of this work (PR 15) it was argued that interpretation of thickener performance by use of basic clarification and thickening theory led to clearer interpretation of the full-scale data on which the analysis was based. Fischerstrom et al. (1967) suggested that the product of the thirty minute sediment volume and the settling velocity be used to evaluate thickener capacity. A discussion of possible inadequacies of this approach was published (PR 6). An extensive study of the relationship between laboratory and full-scale thickening by Edde and Eckenfelder (1967) led to development of a design procedure based on mass loading and two empirical parameters. Study of the method and the nature of the empirical parameters indicated that the approach took into account those basic variables which influence thickening behavior, but that the manner in which the factors were considered was indirect. Hence, the

approach was not considered to provide suitable framework for a rational thickening model.

Probably the most important and most frequently cited work related to thickening is that of Kynch (1952). The applicability of this work to waste sludges was evaluated previously (Dick and Ewing, 1967b). It was found that the work provided a valuable model of the thickening characteristics of ideal suspensions but that the behavior of waste sludges deviated from that of the ideal. Hence, the Talmage and Fitch (1955) geometric procedure for thickener design which is advocated in many text books is not directly applicable to waste sludges because it is based directly on Kynch's work. The approach is further limited by the arbitrary procedure commonly used to identify the limiting concentration.

It was considered that another approach which developed from Kynch's work showed more promise. This was the use of the batch flux plot as advocated by Yoshioka et al. (1957) and Shannon et al. (1963). A limitation of the approach however would be that it does not take into account the effect of depth on settling rates.

Another traditional approach to thickener design which required evaluation was the procedure for determining thickener depth or volume. Conventionally, this has been based on an empirical description of sludge consolidation originated by Roberts (1934). This approach was not considered to be well founded in terms of observed thickening behavior because it involved independent determination of thickener area and thickener depth. It seemed imperative that the design approach take into account the interdependence of the two.

Design Technique

Critical analysis of potential design methods led to selection of an

approach felt to have the greatest utility given to the present state of knowledge of basic thickening properties of waste sludges. The approach is based on earlier work of authors such as Shannon and Tory (1966). The basis of the approach is the rational statement that in a steady state in a continuous thickener, the solids flux, G, is

$$G = c_i v_i + c_i u \qquad (1)$$

where c_i is the suspended solids concentration of sludge at any point in the thickener, v_i is the gravity settling velocity of the sludge at concentration c_i, and u is the downward velocity due to sludge removal. The required solids flux through the thickener is determined by the solids loading and the thickener area, A, such that

$$G = \frac{c_o Q_o}{A} \qquad (2)$$

where c_o and Q_o are the feed concentration and feed rate. Hence, the basis for sizing thickeners is to determine the lowest value of G from equation 1 for all concentrations of sludge which could occur in the thickener and to ascertain that sufficient area is provided so that the value of G from equation 2 does not exceed this limiting value.

This method of thickener analysis is particularly valuable because it takes into account both the settling properties of the sludge and the mode of thickener operation. To explain, the first term in equation 1 is dependent entirely on sludge properties while the second term is determined by operating conditions. The value of the underflow velocity, u, is determined by the rate of sludge removal which depends, in turn, on the desired degree of sludge concentration.

The design approach has been described in more detail in PR 17 which is

included here as Appendix VII. In another publication (PR 11), three possible techniques for solving the basic equations were illustrated, and it was concluded that the approach making use of a batch flux curve had the greatest utility. This paper is reproduced as Appendix VIII. An illustrative problem using the technique is solved on page 123 of Appendix VII, and an illustration of the way which the method can be used as a guide to thickener operation is included on page 124.

The design technique does not require separate determination of thickener depth. Rather, it is necessary that the sludge settling data used in design be representative of those to be expected in the full-scale facility. The effect of depth on the performance or required size of a thickener is evaluated by the use of settling data representative of different sludge depths.

Applications and Extensions of the Technique

The basic thickening model described was used by Barkman (1969) in analysis of the performance of an existing thickener for waste sludge from a water clarification and softening plant. Predictions based on the model were in reasonable agreement with plant operation. The analysis served to reveal that the thickener was being operated at less than its potential capacity. That is, the value of u in equation 1 was needlessly high because sludge was being withdrawn at a faster rate (and lower concentration) than necessary.

The method of analysis for thickener design and operation was applied to the final settling tank of the activated sludge process (PR 11 reproduced as Appendix VIII). It was shown that use of conventional final settling tank design procedures could result in inability to maintain desired suspended solids concentrations in the aeration tank. The approach could be

used as a basis for considering the effects of alternative methods for operating existing tanks or as a basis for optimizing design of new final settling tank.

Results of the laboratory studies of basic sludge thickening mechanisms and the conceptual model of continuous thickener performance afford bases for interpreting results of full-scale thickening studies and for extending and refining the model. Equation 1 permits comparison of velocities in small laboratory batch conditions with those in full scale continuous thickeners, and interpretation of compression in terms of the combined influences of permeability and compressibility (see Chapter II) provides a basis for evaluating the influence of sludge depth and for studying the effects of rakes in thickeners. The first stage of this work is being conducted with a laboratory continuous thickener equipped with means for concentration and excess hydrostatic pressure measurement. This research was inspired by results of work conducted as part of this project, but is being carried out with support from the University of Illinois Water Resources Center.

IV. SUMMARY AND CONCLUSIONS

In spite of the widespread use of sludge thickening in waste treatment, and in spite of the potential for reducing treatment costs by improved thickening, design and operation of thickeners has not been accomplished on a rational basis. The basic goal of this research was to investigate basic thickening properties of sludges and to develop thickener design and operation techniques consistent with knowledge of these properties.

Most results of work carried out in the project have been published in the professional literature. This report serves to summarize and interrelate the various individual reports of work but detailed procedures and results are not repeated. Similarly, general conclusions stemming from the work are presented in this section and more complete conclusions are to be found in the project publications (some of which are included as appendices).

Serious errors can result from the conventional laboratory test for measuring the settling rate of sludges. The influence of slow stirring in laboratory settling tests is not necessarily a reflection of the benefits to be derived by stirring in sludge thickeners, but is caused by the artificial conditions created by the laboratory test. Laboratory tests should be conducted in cylinders as large in diameter as feasible and preferably not less than about 3 in. Sludge depth should be comparable to the effective depth in the full scale facility and a slow stirrer with tip speed of about 10 in./min should be provided.

The sludge volume index is an inadequate, indeed, a misleading, indication of settling characteristics. Its normal use should be restricted to monitoring of gross physical properties of sludge for purposes of routine plant operation. Comparisons should not be made between SVI values of different sludges and more basic and meaningful measures of the physical nature

of sludges should be used in research work.

Deviations in the thickening characteristics of flocculent sludges like activated sludges from those of the ideal slurry considered in Kynch's theory are caused by interparticle contacts. The magnitude of the deviation is related to the yield strength of the sludge.

The final concentration of sludge solids achievable by gravity thickening is controlled by the compressive strength of the sludge. Compressive strength varies exponentially with suspended solids concentration, and hence high concentrations are difficult to attain.

Efforts to increase the final concentration of thickened sludges should be directed at reducing the compressive strength of sludges or increasing the applied compressive load. Greater compressive loads may be achieved by increasing the weight of solids per unit of thickener area; however, the portion of these solids effective in compressing underlying solids is a function of sludge permeability. In work with activated sludge, polymer flocculation did not significantly change the magnitude of interparticle contacts, but rather it altered the discrete settling velocity of the individual floc particles which comprise the sludge. Stirring reduces compressive strength in laboratory settling equipment but may not be of the same significance in full-scale tests.

The rate at which high concentrations are reached in batch sedimentation is a function both of compressibility and permeability. Reduction in sludge permeability yields dual rewards by increasing settling rates and increasing applied compressive loads on underlying sludges.

During thickening, aggregate particles are squeezed to eliminate water and also broken apart. The result is the formation of sludge containing smaller, more numerous, and more dense particles. With sludge exhibiting

poor thickening characteristics, much of the water removed by thickening originates from inside sludge particles whereas more of the water from sludges which thicken well comes from between particles. In either case, the fraction of supernatant water originating from within particles increases as thickening progresses.

With activated sludge, the yield strength in shear (and hence the compressive strength) is increased with increased organic loading intensity. However, it is also highly dependent on the morphology of the organisms comprising the sludge, and two sludges of equal solids concentration developed on the same waste at the same loading intensity may have quite different yield values. Aerobic digestion causes appreciable reduction in yield strength, and pronounced changes occurred following feeding.

Analyses of proposed methods of thickener design indicated that many are inadequate because they fail to take into account those factors which influence thickener performance while others are unsatisfactory because they are based on suspensions with properties different than those encountered in waste treatment. Given the present state of understanding of thickening behavior, the most reliable approach to thickener analysis is a simple statement of continuity in a full-scale thickener. Analyses based on this approach take into account both the settling characteristics of the sludge and thickener operating practices. The batch flux curve affords a convenient technique for evaluating alternative thickener designs or alternative operational modes.

Application of the design approach to the final settling tank of the activated sludge process indicates that use of conventional settling tank design practices can lead to unsatisfactory performance of the entire process. Even when process performance is not affected, failure to consider

the interrelationships between the biological and physical phases of the process leads to uneconomical design.

Full-scale thickener operational practices have an important influence on results. Use of inadequate underflow velocities will become apparent because of solids loss in the effluent. This can be corrected by increasing the rate of sludge removal. However, use of too high an underflow rate must be prevented because it results in the use of facilities at less than full capacity.

REFERENCES*

Project Reports and Publications

PR 1 Babb, M. C.,"An Instrument for the Determination of Sludge Density," Unpublished Special Project Report, 11 pp. (Jan. 1968).

PR 2 Caban, G. L., "Changes in Some Physical Properties of Activated Sludge under High Biological Loading Conditions," NSF Undergraduate Research Project Report, University of Illinois, 71 pp. (Aug. 1969).

PR 3 Chakrabarti, S. K., "Changes in Some Physical Properties of Activated Sludge under Different Biological Loading Conditions," Civil Engineering Studies, Sanitary Engineering Series No. 47, University of Illinois, Urbana, 65 pp. (June 1968).

PR 4 Dick, R. I., "Discussion of In Situ Measurement of Solids in Final Clarifiers by A. E. Albrecht, R. E. Wullschieger, and W. J. Katz," Journal of Sanitary Engineering Division American Society of Civil Engineers, 92, SA5, 117-119 (1966).

PR 5 Dick, R. I., "Discussion of Nominal Diameter of Floc Related to Oxygen Transfer by J. A. Mueller, K. G. Voelkel, and W. C. Boyle," Journal Sanitary Engineering Division American Society of Civil Engineers, 92, SA6, 144-146 (1966).

PR 6 Dick, R. I., "Discussion of Settling of Activated Sludge in Horizontal Tanks by C. N. H. Fisherstrom, E. Isgard, and I. Larsen," Journal Sanitary Engineering Division American Society of Civil Engineers, 93, SA6, 271-273 (1967).

PR 7 Dick, R. I., "Gravity Thickening of Sludge," Summer Institute in Water Pollution Control - Biological Waste Treatment, Manhattan College, Bronx, New York (1968).

PR 8 Dick, R. I., "Some Fundamental Aspects of Sedimentation - the Clarification Function," Water and Wastes Engineering, 6, 2, 47-50 (1969).

PR 9 Dick, R. I., "Some Fundamental Aspects of Sedimentation - the Thickening Function," Water and Wastes Engineering, 6, 3, 44-45 (1969).

PR 10 Dick, R. I., and Ewing, B. B., "Discussion Closure to Evaluation of Activated Sludge Thickening Theories," Journal Sanitary Engineering Division American Society of Civil Engineers, 95, SA2, 333-340 (1969).

PR 11 Dick, R. I., "Role of Activated Sludge Final Settling Tanks," Journal Sanitary Engineering Division American Society of Civil Engineers, 96, SA2, 423-436 (1970) (See Appendix VIII).

*In the text, references to project reports and publications are by number preceded by "PR" whereas other references are cited by use of the name-date system.

PR 12 Dick, R. I., "Discussion of Agglomerate Size Changes in Coagulation by R. K. Ham and R. F. Christman," Journal Sanitary Engineering Division American Society of Civil Engineers, 96, SA2, 624-627 (1970).

PR 13 Dick, R. I., "Discussion of Low Temperature Activated Sludge Settling by S. C. Reed and R. S. Murphy," Journal Sanitary Engineering Division American Society of Civil Engineers, 96, SA2, 638-641 (1970).

PR 14 Dick, R. I., "Thickening Characteristics of Activated Sludge," in Advances in Water Pollution Research, Proceedings of Fourth International Conference on Water Pollution Research, Prague, 1969, 625-642 (1970) (See Appendix III).

PR 15 Dick, R. I., "Formal Discussion of Sedimentation of Activated Sludge in Final Settling Tanks by P. Pflanz," in Advances in Water Pollution Research, Proceedings of Fourth International Conference on Water Pollution Research, Prague, 1969, 583-585 (1970).

PR 16 Dick, R. I., and Javaheri, A. R., "Discussion of Fluidization of Flocs Produced in Chemical or Biological Treatment Plants by F. Edeline, I. Tesarik, and J. Vostreil," in Advances in Water Pollution Research, Proceedings of Fourth International Conference on Water Pollution Research, Prague, 1969, 538 (1970).

PR 17 Dick, R. I., "Thickening," Advances in Water Quality Improvement - Physical and Chemical Processes, E. F. Gloyna and W. W. Eckenfelder, Jr., (editors), University of Texas Press, 358-369 (1970) (See Appendix VII).

PR 18 Dick, R. I., and Vesilind, P. A., "The Sludge Volume Index - What Is It?" Journal Water Pollution Control Federation, 41, 7, 1285-1291 (1969) (See Appendix I).

PR 19 Dick, R. I., Chakrabarti, S. K., and McCutcheon, G. L., "Influence of Biological Variables on Rheological Properties of Activated Sludge," Prepublication Manuscript (1970) (See Appendix VI).

PR 20 Farnsworth, G. A., "The Effect of Induced Flocculation on the Settling and Thickening Behavior of Activated Sludge," Civil Engineering Studies, Sanitary Engineering Series No. 42, University of Illinois, Urbana, 54 pp. (Aug. 1967).

PR 21 Farnsworth, G. A., and Dick, R. I., "The Effect of Polymer Flocculation on the Settling Behavior of Activated Sludge," Prepublication Manuscript (1970) (See Appendix II).

PR 22 Gratteau, J. C., and Dick, R. I., "Activated Sludge Suspended Solids Determinations," Water and Sewage Works, 115, 10, 468-472 (1968).

PR 23 Gain, W. R., "Electrically Induced Settling of Activated Sludge," Unpublished Special Project Report, 29 pp. (Feb. 1968).

PR 24 Gain, W. R., "In Situ Measurement of Suspended Solids Profiles in Sludge Thickeners," M. S. Thesis, University of Illinois, Urbana (currently being prepared).

PR 25 Javaheri, A. R., "Applicability of Two Mathematical Models to the Batch Settling of Activated Sludge," Civil Engineering Studies, Sanitary Engineering Series No. 51, University of Illinois, Urbana, 101 pp. (June 1969).

PR 26 Javaheri, A. R., and Dick, R. I., "Aggregate Size Variations During Thickening of Activated Sludge," Journal Water Pollution Control Federation, 41, 5, Part 2, R197-R214 (1969) (See Appendix IV).

PR 27 Quin, J. R., "Role of Structural Support in Sludge Thickening," Civil Engineering Studies, Sanitary Engineering Series No. 45, University of Illinois, Urbana (May 1968).

PR 28 Shin, B. S., "Distribution of Compressive Forces in Subsiding Sludge Masses," M. S. Thesis, University of Illinois, Urbana (currently being prepared)(See Appendix V).

PR 29 Vesilind, P. A., and Dick, R. I., "Initial Depth as a Variable in Activated Sludge Settling Tests," Effluent and Water Treatment Journal, 9, 5, 263-268 (1969).

PR 30 Wallin, T. R., "The Influence of Ultrasonic Vibrations upon the Physical Features of Activated Sludge," Civil Engineering Studies, Sanitary Engineering Series No. 43, University of Illinois, Urbana, 101 pp. (Nov. 1967).

PR 31 Wang, R. C. T., "A Viscometer for the Study of the Rheology of Activated Sludge," Unpublished Special Project Report, 25 pp. (June 1967).

Other References

American Society of Civil Engineers, "Sewage Treatment Plant Design," Manual of Practice No. 36 (1959).

AWTR Summary Report, Advanced Waste Treatment Research Program, July 1964-July 1967, Federal Water Pollution Control Administration Publication WP-20-AWTR-19 (1968).

Bacon, V. W., nd Dalton, F. E., "Chicago Metro Sanitary District Makes no Little Plans," Public Works, 97, 11, 66 (1966).

Barkman, J. I., "Gravity Thickening and Mechanical Dewatering of Alum-Lime Sludge," Decatur, Illinois, M. S. Special Problem, University of Illinois, Urbana (1969).

Dick, R. I., and Ewing, B. B., "The Rheology of Activated Sludge," Journal Water Pollution Control Federation, 39, 4, 543-560 (1967a).

Dick, R. I., and Ewing, B. B., "Evaluation of Activated Sludge Thickening Theories," Journal Sanitary Engineering Division American Society of Civil Engineers, 93, SA4, 9-29 (1967b).

Edde, H. J., and Eckenfelder, W. W., Jr., "Theoretical Concepts of Gravity Sludge Thickening and Methods of Scale up from Laboratory Units to Prototype Design," Center for Research in Water Resources Report No. 15, University of Texas, Austin, 144 pp. (1967).

Edeline, F., Tesarik, I., and Vostril, J., "Fluidization of Flocs Produced in Chemical or Biological Treatment Plants," in Advances in Water Pollution Research, Proceedings Fourth International Conference, Prague, 1969 , S. H. Jenkins (editor), 523 (1970).

Fischerstrom, C. N. H., Isgard, E., and Larsen, I., "Settling of Activated Sludge in Horizontal Tanks," Journal Sanitary Engineering Division American Society of Civil Engineers, 93, SA3, 73-83 (1967).

Great Lakes - Upper Mississippi River Board of Sanitary Engineers, "Recommended Standards for Sewage Works" (1960).

Ham, R. K., and Christman, R. F., "Agglomerate Size Changes in Coagulation," Journal Sanitary Engineering Division American Society of Civil Engineers, 96, SA3, 481-502 (1969).

Heukelekian, H., and Weisburg, E., "Bound Water and Activated Sludge Bulking," Sewage and Industrial Wastes, 23, 558-574 (1956).

Hurwitz, E., and Katz, W. J., "Concentrating Activated Sludge to a Fuel Value of 4000 BTU per Gallon," Wastes Engineering, 30, 730-733 (1959).

Jordan, V. J., and Scherer, C. H., "Gravity Thickening Techniques of a Water Reclamation Plant," Journal Water Pollution Control Federation, 42, 2, 180 (1970).

Kynch, G. J., "A Theory of Sedimentation," Transactions Faraday Society, 48, 166-176 (1952).

Levin, P., "Disposal Systems and Characteristics of Solid Wastes Generated at Waste Water Treatment Plants," Proceedings 10th Sanitary Engineering Conference, University of Illinois Bulletin 65, 115, 21 (1968).

Mueller, J. A., Voelkel, K. G., and Boyle, W. C., "Nominal Diameter of Floc Related to Oxygen Transfer," Journal Sanitary Engineering Division American Society of Civil Engineers, 92, SA2, 9-20 (1966).

Reed, C., and Murphy, R., "Low Temperature Activated Sludge Settling," Journal Sanitary Engineering Division American Society of Civil Engineers, 95, SA4, 747-767 (1969).

Roberts, E. J., "Colloidal Chemistry and Pulp Thickening," Transactions American Institute of Mining and Metallurgical Engineers, 112, 178-188 (1934).

Shannon, P. T., Stroupe, E., and Tory, E. M., "Batch and Continuous Thickening," Industrial and Engineering Chemistry Fundamentals, 2, 203-211 (1963).

Shannon, P. T., and Tory, E. M., "The Analysis of Continuous Thickening," Transactions American Institute of Mining Engineers, 235, 375-382 (1966).

Shindala, A., Dust, J. V., and Champion, H. L., "Accelerated Digestion of Concentrated Sludge," Water and Sewage Works, 117, 9, 329-332 (1970).

Sleeth, R. E., "Further Experience in the Use of Polyelectrolytes for Sludge Conditioning at Worthing," Effluent and Water Treatment Journal, 10, 10, 582-591 (1970).

Stewart, M. J., "Activated Sludge Process Variables - the Complete Spectrum," Water and Sewage Works, R260-262 (1964).

Talmage, W. P., and Fitch, E. B., "Determining Thickener Unit Areas," Industrial and Engineering Chemistry, 47, 38-41 (1955).

Wood, R. F., "The Effect of Sludge Characteristics upon the Flotation of Bulked Activated Sludge," Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, University of Illinois, Urbana, 143 pp. (1970).

Yoshioka, N., Hotta, Y., Tanaka, S., Nlaito, S., and Tsugami, S., "Continuous Thickening of Homogeneous Flocculated Slurries," Chemical Engineering (Tokyo), 21, 66-74 (1957).

APPENDIX I

THE SLUDGE VOLUME INDEX - WHAT IS IT?

by

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and
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THE SLUDGE VOLUME INDEX—WHAT IS IT?

Richard I. Dick and P. Aarne Vesilind

The sludge volume index (SVI), introduced by Mohlman (1) in 1934, has become the standard measure of the physical characteristics of activated sludge solids. It is defined as "the volume in ml occupied by 1 g activated sludge after settling the aerated liquor for 30 min" (2). The sludge density index, introduced by Donaldson (3), is the reciprocal of the SVI multiplied by 100. Both of these indices originally were intended to be rough measures of sludge settleability to be used in the everyday operation of waste treatment plants as means for monitoring the physical condition of activated sludge. Because of the simplicity of the SVI test, however, it has been applied widely for purposes for which it was not intended originally.

The general acceptance of this arbitrary parameter as a basic measure of the physical properties of activated sludge solids is indicated by its widespread use both in the operation of waste treatment facilities and in research on waste treatment. For example, the SVI commonly is used in research applications to evaluate the effect of biological variables or physical or chemical treatment on the properties of sludge. Also, the SVI has been advocated as a means for establishing the required sludge recirculation rate or for calculating the mixed liquor suspended solids concentration which can be maintained in the aeration tank. The most common use of the parameter, of course, has been in monitoring waste treatment plant operation and in comparing the settling characteristics of various sludges.

In the standard SVI test, sludge volume is observed after a uniformly mixed sample of sludge has settled quiescently for 30 min in a standard 1-l graduated cylinder. The volume occupied by the sludge after this period of settling depends on both the initial settling rate and the subsidence characteristics at the higher sludge concentrations. Two different activated sludges, both of which have the same initial suspended solids concentration and identical 30-min sediment volumes, will have identical SVI values. However, the settling properties of the two sludges may be grossly different (Figure 1). Since the SVI defines only one point on the settling curve, it is not a precise measure of settling characteristics.

If the SVI then is not a measure of the sludge settling characteristics, what is it? What properties of activated sludge influence its magnitude? Does it quantitatively describe physical properties which are indicative of the behavior of the full-scale process? Can meaningful comparisons be made between the values of the SVI in various plants?

The purpose of this paper is to propose answers to the above questions. The limitations of the SVI test are discussed and alternate means

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of describing the basic physical properties of activated sludge are suggested.

Factors Influencing the Sludge Volume Index

Suspended Solids Concentration

If the sludge volume index were some fundamental measure of the solids which comprise activated sludge, then some orderly relationship between the concentration of sludge solids and the sludge volume index would be expected. Sludge volume index determinations were conducted using various concentrations of sludge from several activated sludge plants. The results (Figure 2) indicate that no consistent relationship seems to exist.

The rapid increase of the SVI with increasing concentrations is because of the failure of the sludge to agglomerate into a coarse, open lattice to permit settling. The formation of this open lattice structure, frequently referred to as agglomeration, can be determined readily from observation. The failure to agglomerate is an artifact of cylinder diameter and does not occur necessarily in the full-scale plant (4). For very high suspended solids concentrations [greater than 6,000 mg/l for plants E and A2 (Figure 2)] the sludge still may not agglomerate; but since the maximum possible SVI

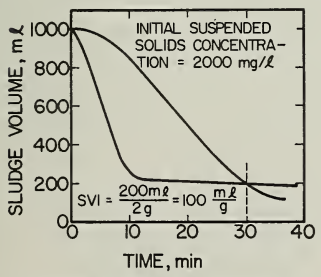

FIGURE 1.—These two sludges, with grossly different settling characteristics, have identical SVI values.

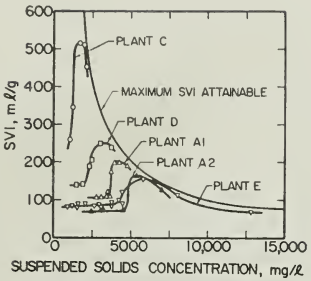

FIGURE 2.—There is no consistent relationship between suspended solids concentration and SVI.

of a sludge decreases as concentration increases, the greater concentrations tend to decrease the SVI. Maximum possible SVI values are shown in Figure 2 as a function of concentration. To illustrate, a sludge of 10,000 mg/l solids, even if it did not settle at all, still would have a maximum SVI equal to 1,000 ml/10g (or 100 ml/g) which generally is considered to be a desirable SVI value. Clearly, therefore, the SVI of a sludge is highly dependent on its suspended solids concentration. SVI values measured at various solids concentrations vary widely (Figure 2). Yet SVI values commonly are compared without regard to concentration.

Rheological Characteristics

Rheological characteristics are fundamental measures of the physical characteristics of a suspension relating to deformation and flow properties. To determine if these properties consistently influence sludge volume index values, the relationships between the SVI and the yield strength and plastic viscosity of various sludges were determined using the viscometer and procedures described by Dick and Ewing (5) (Figures 3 and 4). Sludge yield strength was not related to SVI values in a consistent fashion (Figure

3). Higher SVI values normally were associated with higher plastic viscosities, but the relationship was not the same for all sludges (Figure 4). Thus it was substantiated that SVI is not a reflection of just these basic physical properties.

Interface Velocity

The initial sludge interface velocity obtained in batch settling tests is used widely as an indication of sludge settling characteristics. The relationship between the sludge volume index of sludge samples and their initial settling velocities in one-liter graduated cylinders was explored, and the results (Figure 5) indicate that there is not a consistent, meaningful relationship between the initial settling velocity and the SVI. Attempts also were made to relate the compression rate constant described by Roberts (6) to the SVI. Again, no meaningful correlation was obtained.

Cylinder Diameter

Because the SVI values have been used to predict possible underflow solids concentrations and thus required recirculation rates in full-scale plants, it is appropriate to explore the relationship between settling behavior in the SVI test and in full-scale facilities. The diameter of the standard one-liter cylinder in which SVI measurements are made may influence results. Unless the relationship between settling in small cylinders and settling in full-scale plants can be established, use of SVI values may yield misleading predictions of full-scale settling behavior.

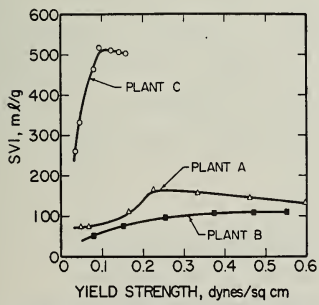

FIGURE 3.—Sludge yield strength does not influence SVI in a consistent manner.

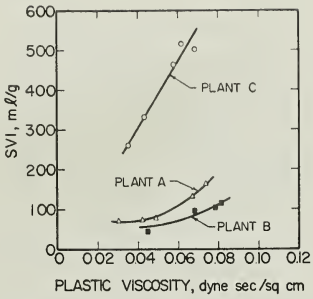

FIGURE 4.—The SVI is not related to plastic viscosity in a consistent manner.

The results of SVI experiments using various sized cylinders (Figure 6) indicate that SVI values can be obtained that are appreciably greater or less than the value associated with the standard cylinder, and that the results from a one-liter cylinder may not be at all indicative of the true sludge settling characteristics. In addition, it does not seem likely that a consistent relationship between SVI and settling in prototype tanks is possible. In this light, it is interesting to note that researchers working with small volumes of sludge often conduct "SVI" measurements in 100-ml graduated cylinders. The effect of cylinder diameter on settling characteristics has been described more thoroughly by Vesilind (7).

Initial Depth

The 1-l graduated cylinders used for the SVI tests are approximately 14 in. (35.6) cm tall. Intial depth,

however, has a considerable influence on the sludge settling rate. For various concentrations of 3 activated sludges, settling velocities in 14-in. (35.6-cm) columns were found to be from 18 to 84 percent of the settling velocities attainable in much taller cylinders (8). The lower settling velocities in short columns are thought to be caused by the increased support provided by underlying solids. Depth affects different sludges differently, indicating that if the settling characteristics of several sludges are to be compared, the tests should be conducted in relatively tall cylinders.

Temperature

The effect of temperature on the settling of sludge was studied by Rudolfs and Lacy in 1934 (9) and their data permit calculation of SVI values (Figure 7). Clearly, the SVI is influenced considerably by the temperature under which the tests are conducted, as would be expected because of viscosity changes. Hence, temperature changes alone can be expected to cause appreciable changes in SVI values. Two sludges with the same SVI value may not be similar if they are taken from two treatment plants with different waste temperatures. Also, seasonal changes in SVI, not related to sludge solids properties, may occur within a given plant.

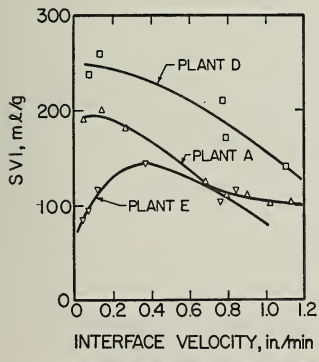

FIGURE 5.—The initial sludge interface velocity, used widely as an indication of sludge settling properties, is not related consistently to SVI.

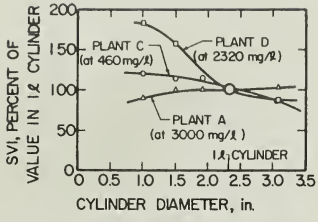

FIGURE 6.—The effect of cylinder diameter on SVI is shown.

Stirring

The effect of stirring on sludge settling is complex. Stirring is thought to (*a*) aid in the agglomeration of the sludge and (*b*) destroy the bridging within a sludge bed in small cylinders. Both of the effects of stirring result in better settling (4).

Because actual settling basins are not quiescent, stirring in test cylinders may tend to yield more realistic results. The results of a series of experiments using slow stirring (1 rpm) (Figure 8) indicate that stirring reduces SVI values significantly. Note that in the stirred tests the SVI still was not independent of the concentration of suspended solids.

The relationship between the quiescent and stirred SVI values is shown on Figure 9. Here the SVI values are expressed as a percent of quiescent test SVI with a value less than 100 indicating a beneficial effect of stirring. All of the sludge tested exhibited better settling under stirred conditions. However the degree of improvement varied with different sludges, and no meaningful correlation existed between the stirred and quiescent tests.

Discussion

The data indicate that sludge volume index is a very nonspecific, arbitrary measure of the physical characteristics of activated sludge. The test does not provide an indication of the settling velocity, since only one point on the settling curve is recorded. Neither is the test a measure of the compactability of the sludge since it is conceivable that, at the end of 30 min, the interface still would be settling at a constant rate. It therefore is difficult to say exactly what the test does measure, and therein lies its major difficulty. It is not related consistently to any basic physical property, but rather represents the combined influence of all of the various physical properties of the sludge. Regrettably, the relative influence of particular physical properties on the SVI changes from sludge to sludge and, indeed, between various concentrations of the same sludge.

In addition, the sludge volume index is not a representative measure of the settling characteristics of sludge in full-scale settling basins because of the artificial settling conditions created in laboratory settling tests. Therefore, it cannot be used quantitatively to predict performance of settling basins.

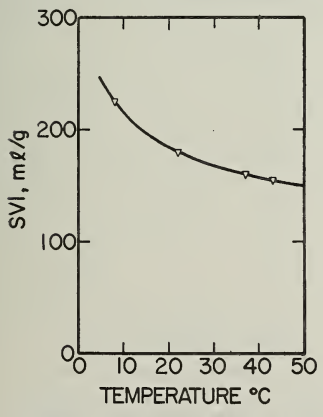

FIGURE 7.—Temperature affects the SVI value of sludge considerably.

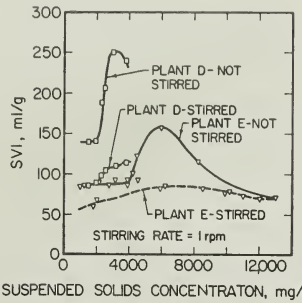

FIGURE 8.—Slow stirring may affect the SVI significantly.

The problems which may result from the misuse of the SVI are numerous. For example, errors inevitably would result if the SVI was used to predict required recycle rates. The selection of design parameters for full-scale treatment plants based on pilot-plant SVI values may result in serious over- or under-design. Research results which rely on the SVI as a primary measure of sludge characteristics may be questionable because of the insensitivity of the SVI to actual changes in the sludge physical characteristics.

What, then, is the value of measuring SVI, and what beneficial use can be made of SVI values? The sole virtues of the determination would seem to be that it can be conducted with relative ease, and through usage, has acquired a "meaning" which permits its use as an operational tool. The determination provides a very convenient test for monitoring changes in performance of a particular plant. Comparisons of SVI values from various plants, however, apparently are meaningless because the test probably measures different properties of different sludges.

Use of the SVI test as an operational tool to monitor changes in sludge characteristics in a given plant would seem to be the only valid application of the measurement. Sludge volume index values based on pilot-plant data cannot be used to calculate the thickening performance of final settling basins or to determine required recycle rates. It would seem particularly inappropriate to use the SVI in research applications. More fundamental measures of physical characteristics are required in these cases.

It is suggested that alternate, more meaningful measurements of the physical characteristics of aetivated sludge be used where possible. One basic measure which can be determined with about the same ease as the SVI is the initial settling velocity associated with various concentrations of aetivated sludge solids. This is determined by finding the slope of the interface subsidence curve of activated sludge solids in a comparatively large stirred settling column. It also may be possible to relate the interface velocities to the concentration by an equation such as $v = ae^{bC}$ where v and C are the interface velocity and concentration, respectively, e is the base of the natural log, and a and b are constants (7). Use of these constants may afford a method by which the settling characteristics of different sludges may be compared.

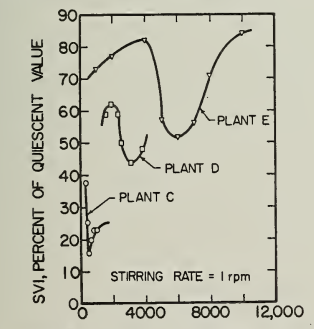

FIGURE 9.—All of the sludges tested exhibited lower SVI values under stirred conditions.

Another possibility, suggested by Dick and Ewing (9), is that rheological measures, such as yield strength and plastic viscosity, be used to describe fundamental physieal properties of activated sludge.

It is realized that some of these alternate methods of measuring sludge properties are influenced by variables such as temperature and concentration just as the sludge volume index is. However, the influence is direct and predictable, whereas the effect of such variables on the SVI is indirect and subtle. This is because the sludge volume index may be influeneed to varying degrees by several physical properties of the sludge, and each of these properties is influenced in a different way by a change in temperature or concentration. A thorough investigation is required, with many different sludges, to develop a test which will be a true measure of the sludge settling characteristics and physical properties. Until better methods are developed, SVI still is a useful test for in-plant control. The value of SVI in research and design applications, however, seems to be limited, and other, more basic measures should be used.

The disadvantages of the alternate parameters suggested for measuring sludge characteristics is that 35 yr of experience are not available to aid in interpreting the meaning of individual measurements as is the case with the sludge volume index. Ultimately, adoption of measures more meaningful than the sludge volume index may be helpful for use in control and improvement of the activated sludge process. Accumulation of experience with more basic measures of sludge properties, perhaps obtained along with SVI measurements, would seem desirable.

Summary

The sludge volume index test does not measure basic physical properties of activated sludge. As an operational tool for in-plant control, the test is useful, but comparisons of sludge volume index measurements from various plants are not meaningful. Results of SVI tests cannot be used with certainty to predict settling behavior in full-scale plants.

Even for in-plant control, alternate measures of settling characteristics probably would be more useful. For research applications, alternate measures of physical properties of activated sludge such as settling velocity, yield strength, and plastic viscosity should be used.

Acknowledgments

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References

1. Mohlman, F. W., "The Sludge Index." *Sew. Works Jour.*, 6, 1, 119 (Jan. 1934).
2. "Standard Methods for the Examination of Water and Wastewater." 12th Ed., Amer. Pub. Health Assn., New York, N. Y. (1965).
3. Donaldson, W., "Some Notes on the Operation of Sewage Treatment Works." *Sew. Works Jour.*, 4, 1, 48 (Jan. 1932).
4. Vesilind, P. A., "The Influence of Stirring in the Thickening of Biological Sludge." Ph.D. thesis, University of North Carolina, Chapel Hill, N. C. (1968).
5. Dick, R. I., and Ewing, B. B., "The Rheology of Activated Sludge." THIS JOURNAL, 39, 4, 543 (Apr. 1967).
6. Roberts, E. J., "Thickening—Art or Science?" *Mining Eng.*, 1, 61 (1949).
7. Vesilind, P. A., "Discussion of Evaluation of Activated Sludge Thickening Theories by R. I. Dick and B. B. Ewing." *Jour. San Eng. Div., Proc. Amer. Soc. Civil Engr.*, 94, SA1, 185 (1968).
8. Dick, R. I., and Ewing, B. B., "Evaluation of Activated Sludge Thickening Theories." *Jour. San. Eng. Div., Proc. Amer. Soc. Civil Engr.*, 93, SA4, 9 (1967).
9. Rudolfs, W., and Lacy, I. O., "Settling and Compacting of Activated Sludge." *Sew. Works Jour.*, 6, 4, 647 (July 1934).

APPENDIX II

THE EFFECT OF POLYMER FLOCCULATION ON THE SETTLING BEHAVIOR OF ACTIVATED SLUDGE

by

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and
Richard I. Dick

Prepublication Manuscript

THE EFFECT OF THE DEGREE OF FLOCCULATION ON THE BASIC SETTLING BEHAVIOR OF ACTIVATED SLUDGE

George A. Fransworth and Richard I. Dick

The efficiency, mode of operation, and cost of treatment by the activated sludge process depend to a considerable degree on the efficiency of the final settling operation. It follows that if close control and economical design of the process are to be achieved, settling tank design practices should be based on a firm conception of the fundamental factors governing the settling and thickening of activated sludge. The more practicable aspects of final settling tank design and the influence of the design on the overall activated sludge process have been considered elsewhere (Dick, 1970b). The work reported here (Farnsworth, 1967) was part of a more fundamental investigation of the settling properties of activated sludge.

ACTIVATED SLUDGE SEDIMENTATION

Sedimentation of a concentrated "ideal" suspension comprised of particles of uniform size and shape has been described by Kynch (1952). His model has been shown to provide an accurate description of the sedimentation of suspensions such as glass beads (Shannon and Tory, 1965) and sand grains (Dick and Ewing, 1967) in which fluid drag and gravity are the only forces acting on the particles. However, considerable deviations from Kynch's theory have been found with flocculant suspensions such as clay (Gaudin and Fuerstena, 1962) and activated sludge (Dick and Ewing, 1967).

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Dick and Ewing (1967) showed that existence of a continuous structure within activated sludge even at normal mixed liquor suspended solids concentrations caused a dependence of settling velocity upon sludge depth. Experimentally, they found the relationship between sludge depth, D, and settling velocity, v, to be

$$v = \frac{D}{SD + R} \tag{1}$$

where R is the intercept on the ordinate axis of a plot of D/v as a function of D and S is the slope of the curve. The form of the relationship has been confirmed by Vesilind (1968) and others. When R in equation (1) is zero or as D approaches infinity,

$$v = v_u = \frac{1}{S} \tag{2}$$

where v_u is the "ultimate settling velocity" or the velocity at which the interface would subside if it received no support from underlying sludge. Hence, the reciprocal of S is a measure of the settling velocity of sludge if it conformed to Kynch's theory, and R, called the retardation factor, is a measure of the deviation of settling characteristics from those of an ideal suspension. The retardation factor has been found (Dick and Ewing, 1967) to vary with suspended solids concentration, e, according to the relationship

$$R = ge^{hc} \tag{3}$$

where g and h are constants for a given sludge.

OBJECTIVES

The objective of the study was to determine the effects of changes in the degree of flocculation of activated sludge on its settling characteristics. An extent of flocculation was adjusted by adding a synthetic organic

polyelectrolyte and the effect on zone settling velocity as a function of initial sludge depth was observed in order to determine the ultimate settling velocity and retardation factor for each condition of flocculation.

Inasmuch as the value of g in equation (3) must be zero for an ideal suspension, and because the values of g and h were previously found to be related to the biological (Dick and Ewing, 1967) and rheological (Dick, 1970a) characteristics of the sludge, it was anticipated that the effect of the degree of flocculation on the settling characteristics of activated sludge might be interpreted in terms of the effects on the constants in equation (3).

The main purpose of the work was to gain insight into the factors which control the basic physical behavior of activated sludge. Some information on the possible benefits of polymer induced sludge flocculation and on the interpretation of sedimentation tests using polymer conditioned sludge were also obtained.

PROCEDURES

A major difficulty in the work was to express quantitatively the degree to which sludge solids were agglomerated. Because the degree of flocculation relates to the extent to which the sludge solids agglomerate, and because this in turn influences the clarity of the liquid eliminated, turbidity of the supernatant liquid was used as a measure of the degree of flocculation This parameter has been found by others to be sensitive to changes in flocculent dose (for example, by Black and Chen, 1965). It must be admitted however that use of the turbidity measurement was primarily an expedient dictated by the lack, at present, of a better measure of the degree of flocculation. A nephelometer[a] was used for turbidity measurements.

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[a]Model 1800 manufactured by the Hach Chemical Col, Ames, Iowa.

All sludge used in the study was taken from the Urbana-Champaign, Illinois Sanitary District main treatment plant. The effect of varying doses of a cationic polyelectrolyte, purifloc C31,[b] on flocculation of the activated sludge is illustrated in Figure 1. Data are from tests in a six-place jar test apparatus[c] using 15 min at 30 rpm followed by 30 min of quiescence. For purposes of this study, flocculant doses in the initial steep portion of the curve preceding the dosage for optimum flocculation were used in order to achieve maximum differences in the degree of flocculation. As would be expected, pH exerted a significant influence on flocculation. pH was monitored throughout the study to ascertain that all tests were conducted at the same value (7.1); however, pH adjustment was not found to be necessary.

Sedimentation tests were conducted in 3.5 in. diameter settling columns using the equipment and procedures described by Dick and Ewing (1967). The suspended solids were determined using the Gooch crucible-glass fiber filter method described by Gratteau and Dick (1968).

To assure that all tests were conducted on a sludge with the same basic physical properties, it was necessary to obtain all sludge used in the tests at one time and to complete the experiments in as short a period as possible. These requirements limited the study in two ways. Firstly, the number of different flocculent conditions had to be limited to three (0.0, 0.97, and 2.43 mg/purifloc C31/g sludge solids). Secondly, it was necessary to reuse sludge dosed with polymer for all settling tests at a given polymer dosage. Polymer was applied to the most concentrated sludge

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[b] A product of Dow Chemical Co., Midland, Michigan.

[c] Manufactured by the Phipps and Byrd Co., Richmond, Virginia.

sample and lesser concentrations were achieved by adding supernatant liquid from settled undosed sludge and mixed by aeration. It was recognized that reuse of dosed sludge was highly undesirable; however, random duplication of settling tests gave similar results.

At each of the three flocculent conditions, settling tests were conducted at four different suspended solids concentrations. At each suspended solids concentration, five or six settling tests at various depths between 1 and 6 ft were used to define the relationship between settling velocity and depth. Also, two 3.5 ft control depths were obtained at each concentration to monitor for any temporal variation in sludge quality.

RESULTS AND DISCUSSION

At all degrees of flocculation and at all suspended solids concentrations the data conformed well to equation (1). Values of the retardation factor, as given by application of that formula, are shown for each of the three flocculent conditions in Figure 2. The influence of the degree of flocculation on the ultimate settling velocity (1/S) is illustrated in Figure 3. It is seen that the effect of flocculation was on the ideal settling velocity of the sludge particles and not on the extent of deviation from ideal conditions (as measured by the retardation factor). This suggests that the structural forces between particles are not significantly influenced by polymers. This is consistent with results reported by Dell and Keleghan (1970) who found that neither flocculent type nor dosage influenced the compressibility of clay suspensions.

The fact that polymers influence ultimate settling velocity but not the retardation factor means that the beneficial effect of polymers will be masked at shallow sludge depths if sludges have an appreciable retardation factor. This is illustrated in Figures 4 and 5 where the effect of polymer

dosage on settling velocity at 5.0 and 2.5 ft initial depths is illustrated. Clearly, the difference between flocculated and unflocculated samples decreased as depth diminished. This means that in laboratory evaluation of the feasibility of polymer addition it would be important to use effective depths comparable to those expected in the field.

It is interesting to note that the influence of polymers on the settling characteristics of the activated sludge was highly dependent upon suspended solids concentration (Figures 3, 4, and 5). With the particular sludge used, polymers improved settling velocity for concentrations less than about 5250 mg/l but caused reduction in settling velocity at higher concentrations.

SUMMARY AND CONCLUSIONS

The influence of the degree of flocculation of activated sludge was investigated to gain insight into the factors which control the fundamental physical properties of the material. A synthetic organic polyelectrolyte was used to vary the degree of flocculation, and settling velocity was the principal physical property observed.

Flocculation significantly effects sludge interface settling velocity at large sludge depths and has less effect on settling velocity at low depths. This means that the principal effect of the degree of sludge flocculation is on the ultimate settling velocity of sludge and not on the magnitude of interparticle forces (or the retardation factor). While the purpose of this study was not to investigate the feasibility of using artificial flocculents in the activated sludge process, several cautions can be offered to those who are working in this area. Influence of polymers on settling velocity depends on sludge depth and hence laboratory tests must be conducted at effective depths comparable to those expected in the field. Furthermore,

the same polymer may improve settling characteristics of sludge at one concentration but cause slower settling at another concentration. Hence, an evaluation must extend over a wide range of suspended solids concentrations.

Implications of the work are that polymer conditioning of activated sludge will not appreciably alter the concentration of sludge which is ultimately achievable by gravity thickening. However, the capacity of a thickener may be increased by polymer flocculation because settling velocities may be enhanced, and the concentration of the underflow from an activated sludge final settling tank may be increased if the tank is not operating near the ultimately achievable concentration.

ACKNOWLEDGEMENTS

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REFERENCES

Dell, C. C. and Keloghan, W. T., "Compressibility of Flocculated Clay Suspensions," Filtration and Separation, 7, 4, 419-421 (1970).

Dick, R. I., "Thickening Characteristics of Activated Sludge," in Advances in Water Pollution Research, Proceedings of Fourth International Conference on Water Pollution Research, Prague, 1969, 625-642 (1970a).

Dick, R. I., "Role of Activated Sludge Final Settling Tanks," Journal Sanitary Engineering Division American Society of Civil Engineers, 96, SA2, 423-436 (1970b).

Dick, R. I., and Ewing, B. B., "Evaluation of Activated Sludge Thickening Theories," Journal Sanitary Engineering Division American Society of Civil Engineers, 93, SA4, 9-29 (1967).

Farnsworth, G. A., "The Effect of Induced Flocculation on the Settling and Thickening Behavior of Activated Sludge," Civil Engineering Studies, Sanitary Engineering Series No. 42, 54 pp (1967).

Gaudin, A. M., and Fuerstena, N. C., "Experimental and Mathematical Model of Thickening," Trans. Society Mining Eng., 223, 122-229 (1962).

Gratteau, J. C., and Dick, R. I., "Activated Sludge Suspended Solids Determinations," Water and Sewage Works, 115, 10, 468-472 (1968).

Kynch, G. J., "A Theory of Sedimentation," Trans. Faraday Society, 48, 166-176 (1952).

Shannon, P. T., and Tory, E. M., "Settling of Slurries," Industrial and Engineering Chemistry, 57, 18-25 (1965).

Vesilind, P. A., "The Influence of Stirring in the Thickening of Biological Sludge," Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, University of North Carolina (1968).

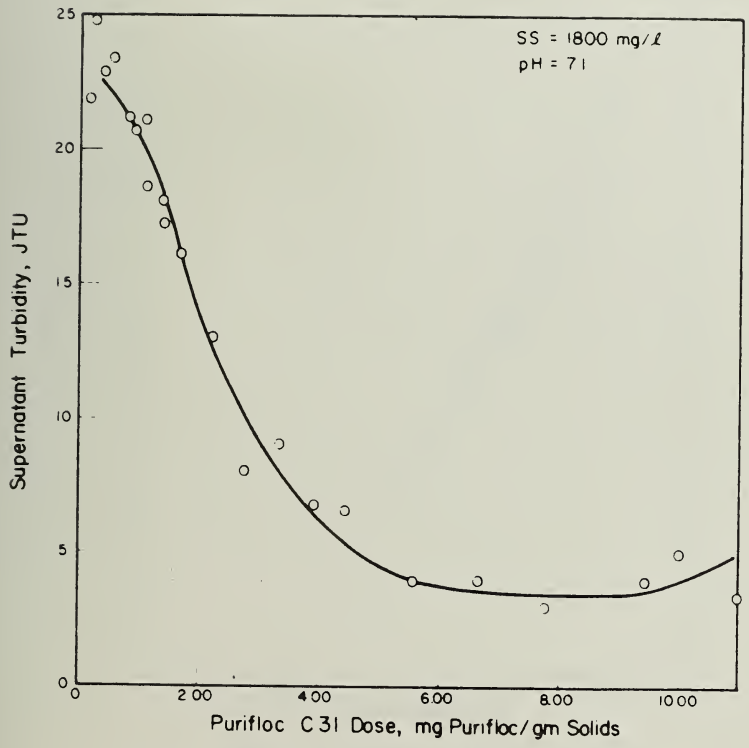

Fig. 1 Effect of Polymer Dose on Degree of Flocculation

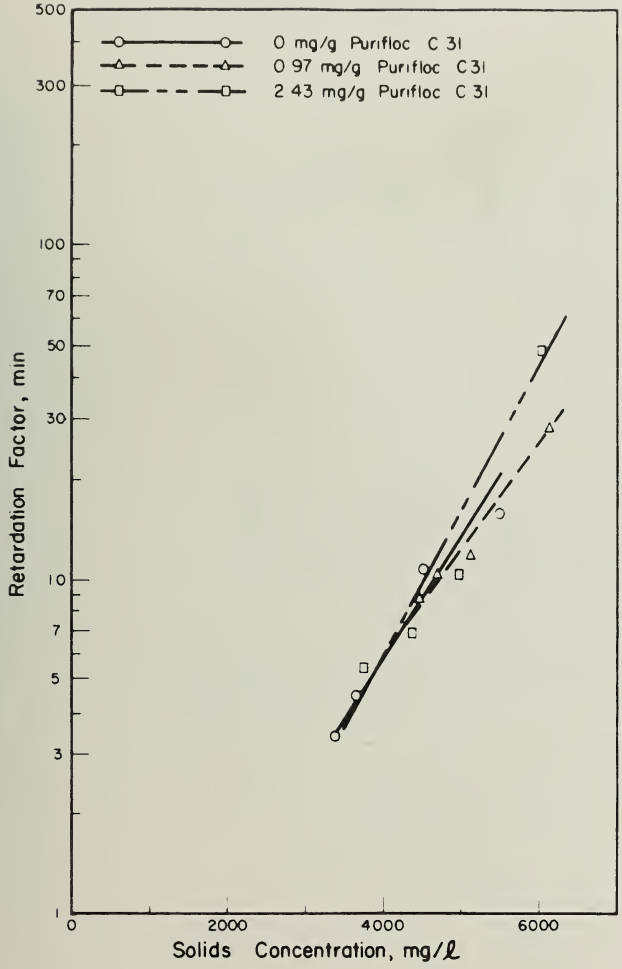

Fig. 2 Relation Between Suspended Solids Concentration and Retardation Factor

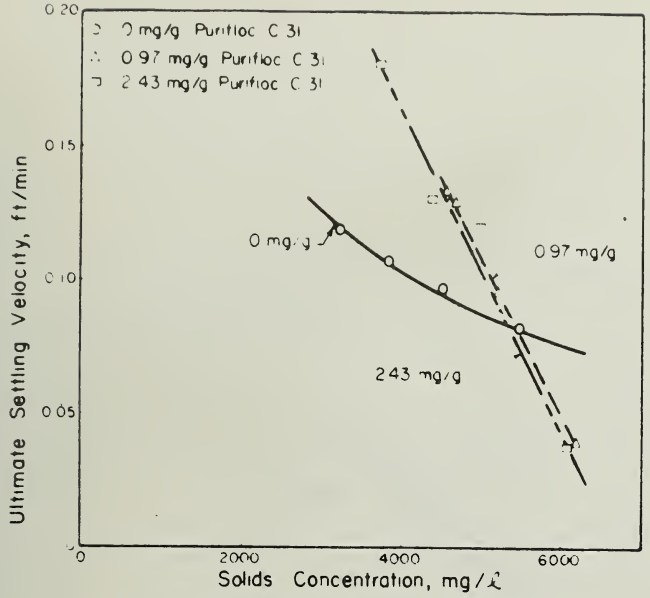

Fig. 3 Influence of Degree of Flocculation on Ultimate Settling Velocity

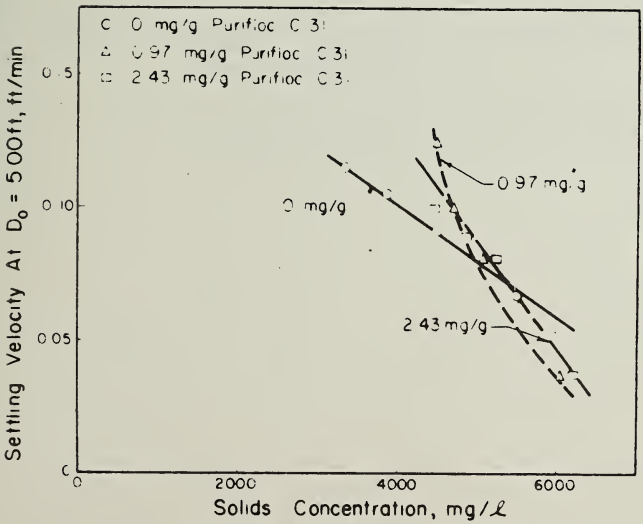

Fig. 4 Influence of Degree of Flocculation on Settling Velocity at an Initial Sludge Depth of 5.00 ft

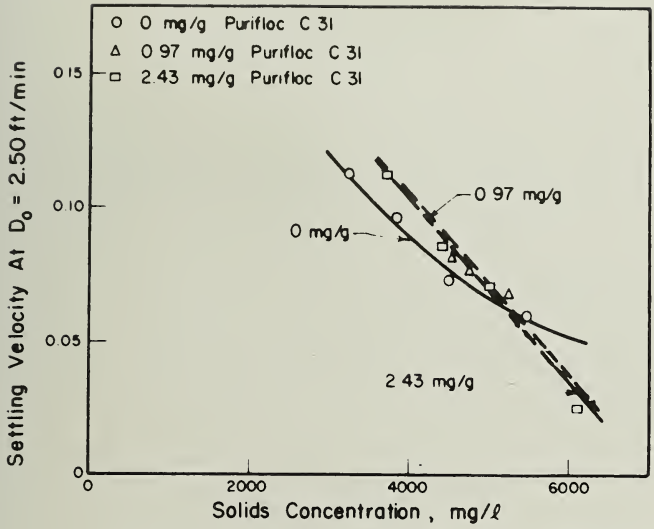

Fig. 5 Influence of Degree of Flocculation on Settling Velocity at an Initial Sludge Depth of 2.50 ft

APPENDIX III

THICKENING CHARACTERISTICS OF ACTIVATED SLUDGE

by

Richard I. Dick

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THICKENING CHARACTERISTICS OF ACTIVATED SLUDGE

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INTRODUCTION

Consolidation of sludge to high concentrations in the final settling tank is necessary for economical performance of the activated sludge process. The amount of organic material which can be applied to an activated sludge treatment plant depends on the mixed liquor suspended solids concentration, and this concentration is related to the degree of thickening accomplished in the final settling tank. Furthermore, the cost of disposing of the excess solids synthesized in the process depends on the concentration at which they are wasted from the final settling tank.

Improvement in the ability of final settling tanks to accomplish their clarification and thickening functions could decrease significantly the cost of new plants and increase the capacity of existing ones. A basic understanding of the settling behavior of activated sludge must be acquired to permit development of rational and workable design criteria to accomplish such improvement. Attention is given in this paper to basic factors which influence the solids handling capacity of activated sludge.

CONVENTIONAL THEORIES OF THICKENING

Coe and Clevenger (1916) introduced the concept of solids handling capacity. Each concentration of a suspension was shown to have a certain capacity to discharge its solids. The minimum, or limiting, solids handling capacity of the suspension must be used to establish the area of a settling basin if thickening of underflow to the desired concentration is to be accomplished. If insufficient area is provided, the solids will queue above the location of the rate-limiting concentration of the suspension, and ultimately pass over the effluent weir along with the "clarified" effluent.

Confirmation and clarification of Coe and Clevenger's concepts were provided by Kynch (1952). He presented a mathematical analysis of thickening based, not on consideration of fundamental factors controlling subsidence of suspensions, but, rather, on the arbitrary assumption that "at any point in a dispersion the velocity of fall of a particle depends only on the local concentration of particles." The analysis serves as the fundamental basis for present practices for determining the required area of thickeners.

When concentration increases to the extent that particles begin to rest on one another (when the "compression point" is reached) different thickening concepts are presumed to apply (Roberts, 1949). While the solids handling capacity of the "freely" settling suspension is considered to establish the required area of a thickener, consolidation characteristics are considered to dictate the volume required. This paper only deals with matters related to the area requirement.

More complete reviews of conventional thickening theories have been presented by Behn (1957), Fitch (1962), and Dick and Ewing (1967b).

APPLICABILITY OF THICKENING THEORIES

The Kynch analysis forms a valuable framework for understanding the behavior of freely settling suspensions. For suspensions which conform to Kynch's assumptions, the analysis affords a precise description of settling behavior (Shannon *et al.*, 1964, Dick and Ewing, 1967b). Suspensions with physical characteristics which are less ideal may not conform to settling behavior predicted by the Kynch analysis because they violate assumptions on which the mathematical analysis is based. Still the Kynch analysis serves as a valuable basis for identifying deviant settling behavior and for intercepting causes of such deviations.

The settling behavior of activated sludge has been found to be inconsistent with the Kynch analysis (Dick and Ewing, 1967b). The initial "free' constant-rate settling velocity of comparatively dilute concentrations of activated sludge varies with sludge depth according to the expression

$$v_i = \frac{D}{R + SD} \tag{1}$$

where D is the initial depth of uniformly dispersed sludge, and R and S are constants which characterize the settling behavior of a given concentration of a particular activated sludge. The magnitude of R, the retardation factor, is a measure of the extent to which the settling velocity of activated sludge is retarded by causes not considered in the Kynch analysis. The settling velocity that a sludge would have if it settled like the ideal suspension in prevalent theories of thickening is given by $1/S$ and is termed the ultimate settling velocity, v_u. If settling velocity depended only on concentration in accordance with prevailing concepts, there would be no dependence on depth; that is R would be zero.

An appreciation of the significance of this deviant settling behavior of activated sludge may be gained from Fig. 1 where observed settling velocities for several activated sludges are plotted as a percentage of v_u. The purpose of the present study was to investigate the cause of this non-deal settling behavior.

THICKENING MODEL

To assume, with Kynch, that the settling velocity of a given suspension is a function only of local particle concentration is equivalent to assuming that only fluid forces act on sludge particles. Although Kynch did not explore the nature of these forces, the relationship between particle concentration and settling velocity of suspensions has been developed by others—notably Vand (1948). Inasmuch as the settling characteristics of activated sludge do not conform to these concepts, even at suspended solids concentrations found in mixed liquor, it is necessary to introduce additional forces which act on sludge particles to influence their settling behavior. In this conceptual model, the additional forces of significance are considered to be forces transmitted through interparticle contacts. Conventionally such forces are not considered to exist until the compaction point is reached and compression begins.

Figure 2 shows a mass of sludge of unit cross-sectional area and depth, D, along with representation of the forces considered to be acting on the sludge. The free body diagram shows the sludge at the onset of sedimentation when the solids are uniformly distributed. The sludge is considered to settle *en masse* with floc particles maintaining their relative positions one to another. As sedimentation occurs, the flocculent structure

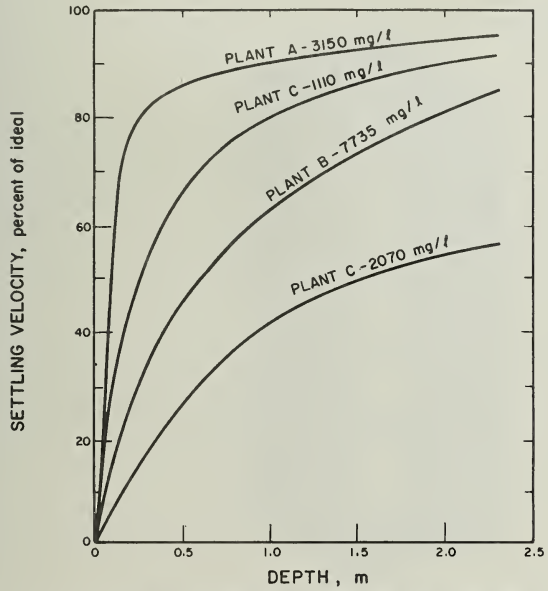

FIG. 1. Extent of deviation of activated sludge settling behavior from that of an ideal suspension

is envisioned to collapse against the bottom of the container. Acceleration is considered to have ceased so that the net force on the sludge mass is zero, or

$$F_W = F_B + F_D + F_S \tag{2}$$

where F_W is the downward force due to weight of sludge solids, F_B is the upward force due to buoyancy, F_D is the drag force resisting downward movement of sludge, and F_S is the resistance to subsidence due to the compressive strength of the structure of flocculent particles.

The forces due to the weight and buoyancy of the sludge may be combined in a single force, F_E, representing the effective weight of the solids in the liquid. For a particular

sludge, the effective weight of solids per unit cross-sectional area will vary directly with depth and concentration, so that

$$F_E = K_1 c D \tag{3}$$

where the constant, K_1, includes basic physical properties of the solids and suspending liquid.

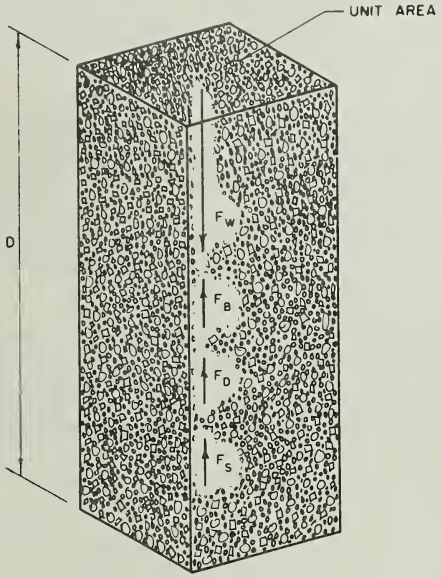

FIG. 2. Definition sketch for thickening model

The drag force acting on the descending sludge, or, its equivalent, the resistance offered by the sludge particles to the escape of displaced fluid, depends on the nature of the flow regime. It is estimated that the order of magnitude of Reynolds number for flow through activated sludge is near the approximate upper limit for laminar flow through porous media. On this basis, it would be expected that, in the microstructure of flow through sludge, localized, turbulence occurs to the extent that inertial forces contribute significantly to the total drag on the sludge mass (Schneebeli, 1955). In the absence of precise knowledge of the flow regime, versions of the model were developed for both laminar and turbulent flow to describe the two possible extremes in fluid behavior. The subscripts L and T are used to distinguish the two versions.

The value of F_D with laminar interstitial flow may be expressed as the sum of drag forces on the individual floc particles which comprise the sludge mass. The general expression for the drag resisting movement of a body through a fluid,

$$F_D = C_D A \frac{P_W v_L^2}{2} \tag{4}$$

may be applied. In laminar flow the coefficient of drag, C_D, is related inversely to Reynolds number, and hence drag varies with the first power of velocity. Also, for a single concentration of a particular sludge the collective projected area of the flocculated particles in the sludge mass, A, is a direct function of depth. Hence*

$$F_{D_L} = K_2 D v_L \tag{5}$$

where K_2 reflects physical properties of the fluid and parameters related to the flocculent nature of the sludge and is constant only for a particular sludge at a single concentration and temperature, and v_L is a representative velocity which may be taken as the interface subsidence rate.

If, as an extreme, displaced liquid is considered to escape by fully-developed turbulent flow, fluid drag becomes independent of Reynolds number and hence is proportional to the square of the subsidence velocity, or†

$$F_{D_T} = K_3 D v_T^2 \tag{6}$$

The constant reflects physical properties of the suspending medium and physical characteristics of the solids which establish the size of flow channels and is constant only for one concentration of a given sludge.

The subsidence rate of the sludge mass may be evaluated by combining equations (2), (3) and (5) (or 6). For the laminar flow model,

$$v_L = \frac{K_1}{K_2} c - \frac{F_S}{K_2 D} \tag{7}$$

and for the turbulent flow model,

$$v_T = \sqrt{\left(\frac{K_1}{K_3} c - \frac{F_S}{K_3 D}\right)} \tag{8}$$

CHARACTERISTICS OF THICKENING MODEL

In either the laminar or turbulent flow model, settling velocity is dependent solely on particle concentration (in accordance with the Kynch analysis) only when the second term on the right side of equations (7) and (8) is insignificant. Settling velocity is also a function of depth whenever the suspension possesses structure which must collapse to permit subsidence. The extent of retardation caused by a given value of F_S is dependent upon the magnitude of K_2 (or K_3 in the turbulent version). A suspension

* If it is preferred to visualize laminar flow in subsiding sludge as analogous to flow through porous media, equation (5) may be derived from Darcy's law.

† Equation (6) may also be derived from the Darcy–Weisbach expression for flow through pipes

which settles slowly in the absence of retardation due to F_S will be relatively less affected by structural retardation than one which settles rapidly when unretarded.

Figure 3 shows the basic form of either version of the model. The deviation from prevailing thickening theory when F_S has a finite value and the resemblance of the deviant behavior to observed activated sludge settling characteristics is illustrated.

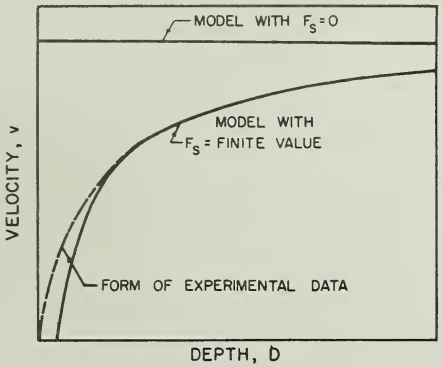

Fig. 3. General form of thickening model

The model is, however, somewhat defective in that it indicates that, at some small depth, sludge will stand without settling. This occurs when the depth is so small that the effective weight of the sludge equals the structural support force. Then the drag force—and hence the settling velocity—must equal zero. Although experimental determination of settling velocities of shallow depths of activated sludge is difficult, a zone of clarified water develops in time at the top of the shallowest of sludge depths.

The defect in the model is understandable. Consolidation of the structure within activated sludge is probably a viscoelastic process which continues at low loadings (i.e. shallow depths) by the process of creep or plastic flow. From time to time connections between adjacent floc particles may break and reform in an unstressed position. This results in a redistribution of interparticle stresses and contributes to subsequent failure of other connections.

The time-dependent failure of the structure of activated sludge is likely related to its lyophilic nature. Particles in activated sludge probably are not in actual contact, but are separated by liquid films. The deformation characteristics of sludge might, then, be related to the nature of the interparticle films rather than, or in addition to, mechanical properties of the particles. Such films are comprised of water which has a high degree of orientation and exists in a quasi-solid state (Frank and Evans, 1945). A matrix of such quasi-solid films could account for the difference between observed settling behavior and the form of the model, for deformation to permit subsidence would occur under all conditions—not just when the equivalent weight of sludge exceeded F_S.

COMPARISON WITH EXPERIMENTAL SETTLING DATA

For convenience, equations (7) and (8) may be written as

$$v_L = a_L - \frac{b_L}{D} \tag{9}$$

and

$$v_T = \sqrt{\left(a_T - \frac{b_T}{D}\right)} \tag{10}$$

where the values of a and b are apparent from comparison with the previous equations. Direct determination of the constants a and b is not possible, for F_S, K_2, and K_3 cannot be evaluated directly. The values of a and b, however, can be computed from the experimentally determinable parameters R and S (equation 1).

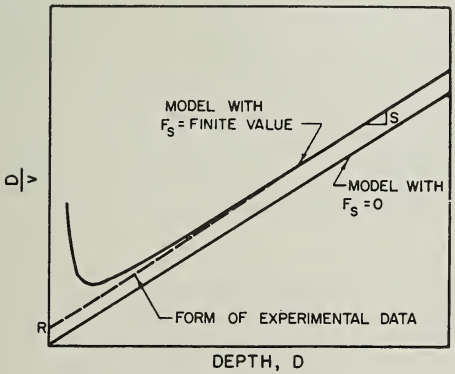

FIG. 4. Form of D/v vs. D plots

From equation (1) it is seen that S is the slope of a plot of D/v as a function of D, and R is the intercept on the D/v axis as illustrated in Fig. 4. In terms of the laminar flow model, then,

$$S_L = \frac{d}{dD}\left(\frac{D}{v_L}\right) = \frac{d}{dD}\left(\frac{D}{a_L - \frac{b_L}{D}}\right) \tag{11}$$

Differentiation gives

$$S_L = \frac{a_L D^2 - 2b_L D}{(a_L D - b_L)^2} \tag{12}$$

Because of the defect described in the previous section, S_L is not a constant, but is depth dependent (the D/v vs. D plot for the model only asymptotically approaches

the straight line found experimentally). The retardation factor, R, for the model may be taken as the back extrapolate of the tangent to any point on the curve in Fig. 4. Thus,

$$R_L = \frac{D}{v_L} - DS_L \tag{13}$$

Substituting equations (9) and (12) and simplifying gives

$$R_L = \frac{b_L D^2}{(a_L D - b_L)^2} \tag{14}$$

The values of S and R for the turbulent model may be derived in a similar fashion.

Representative batch settling tests at various initial sludge depths were conducted to generate D/V vs. D plots for various concentrations of several activated sludges. Values of R and S were then determined from the data and a and b were evaluated by simultaneous solution of equations (13) and (14) (or their counterparts in the turbulent version) for selected values of D. Typical results are shown in Figs. 5 and 6 for two concentrations of activated sludge from a treatment plant designated as A.

Because the constants in the model were computed from observed data, the figures do not constitute confirmation of the validity of the model. However, they demonstrate the basic agreement of the form of the model with experimental data. At low degrees of retardation (Fig. 5, $R = 0.8$ min) differences between the experimental and model curves due to the defect in the model were minimal, while differences become more pronounced with higher degrees of retardation (Fig. 6, $R = 6.3$ min).

Relationship between settling and rheological behavior

To confirm the validity of the thickening model, it is necessary to show that activated sludge does, indeed, possess internal structure at comparatively dilute suspended solids concentrations and that the effect of such structure is quantitatively described by the model. To do this, sedimentation and rheological properties of activated sludge from three municipal activated sludge plants of widely varying characteristics were examined concurrently. The experiments were conducted over the range of suspended solids concentrations which might occur in the final settling tank in the plant from which each sludge was collected. Table 1 shows the conditions which existed in the three waste treatment plants at the time samples were obtained.

Table 1. Properties of Activated Sludges Used

Source of sludge	Suspended solids concentration mg/l.		Sludge volume index (ml/g)	Organic loading g B.O.D./day
	Mixed liquor	Return sludge		g sludge solids
Plant A	2280	8230	75	0.14
Plant B	4350	7420	55	0.06
Plant C	1225	2820	300	1.35

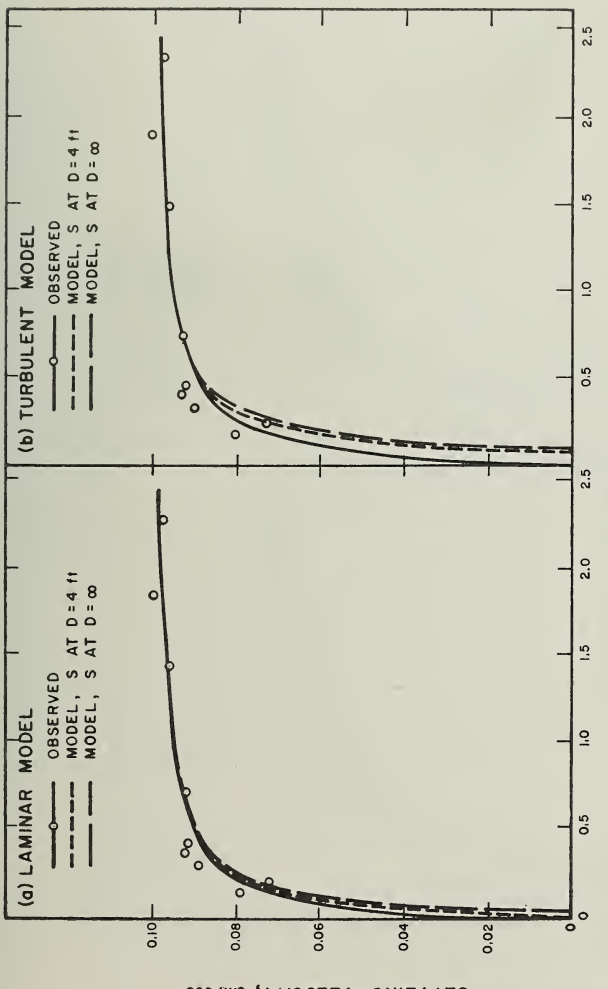

FIG. 5. Comparison of model form and observed behavior. Activated sludge from plant A at 2400 mg/l.

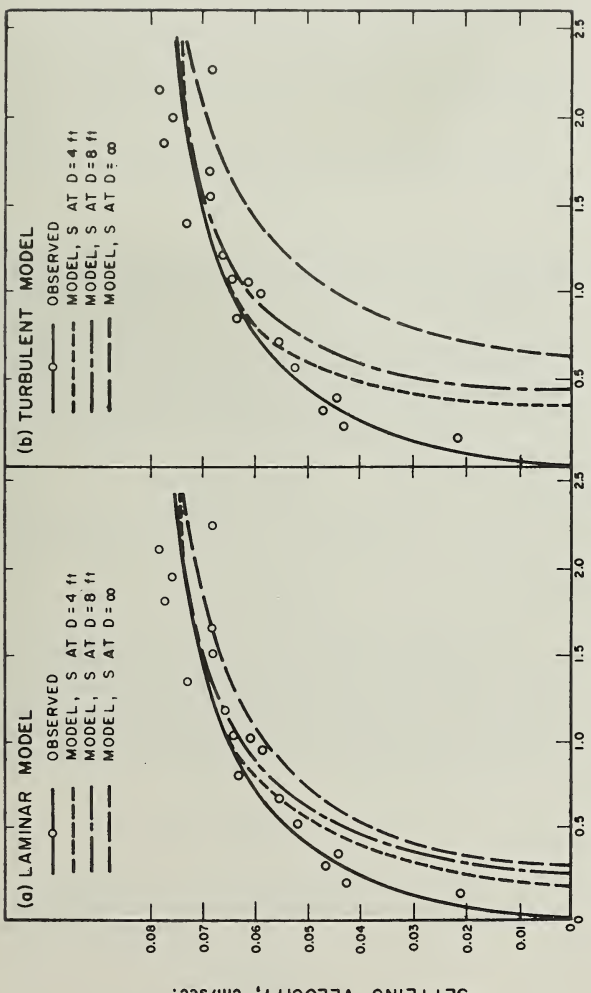

Fig. 6. Comparison of model form and observed behavior. Activated sludge from plant A at 4210 mg/l.

The sedimentation properties of interest were those which measure the deviations from ideal settling behavior—R and S. The comparative settling characteristics of the three sludges have been described previously (Dick and Ewing, 1967b).

The rheological property of interest was one which could account for internal rigidity—the yield strength. Measurements were made with a viscometer adapted for use with activated sludge. Results of the rheological studies are described elsewhere (Dick and Ewing, 1967a).

For all sludges both the yield strength and retardation factor varied exponentially with suspended solids concentration. It follows that a relationship of the form

$$R = m\tau_y^n \tag{15}$$

relates R and the yield strength, τ_y, of activated sludges where m and n are constants. Figure 7 illustrates the relationship. The equation does not, however, necessarily show a cause-and-effect relationship but could merely reflect a mutual dependence on suspended solids concentration.

A more meaningful indication of the relationship between observed settling behavior and the rheological properties of sludge can be obtained by modifying the mathematical expression of the thickening model to give a relationship between yield strength and thickening properties. In the case of the laminar version of the model, the equality of the denominators in equations (12) and (14) results in

$$\frac{a_L D^2 - 2b_L D}{S_L} = \frac{b_L D^2}{R_L} \tag{16}$$

Simplifying and substituting the expressions for a_L and b_L gives

$$F_{S_L} = K_1 \left(\frac{cDR_L}{S_L D + 2R_L} \right) \tag{17}$$

All values on the right side of the equation can be determined experimentally.

It remains to express the structural support force in terms of yield strength. Although a quantitative relationship between the yield strength of a substance in shear and its confined compressive strength cannot be rigorously formulated, it is reasonable to expect that the same properties which determined the yield strength of a suspension are related to the structural support force, F_S. If the relationship is presumed to be linear

$$\tau_{y_L} = K_4 \left(\frac{cDR_L}{S_L D + 2R_L} \right) \tag{18}$$

in which K_4 is K_1 modified to account for the relationship between F_S and τ_y. Similar derivation of the relationship between the settling and rheological parameters in the turbulent version of the model gives

$$\tau_{y_T} = K_4 \left(\frac{2cDR_T}{S_T D + 3R_T} \right) \tag{19}$$

The agreement between the rheological properties of activated sludge as measured in the viscometer and as computed from observed settling data based on the thickening model is illustrated in Fig. 8 and 9. The absolute value of the quantity plotted on the abscissa is irrelevant since the value of the constant, K_4, which relates it to τ_y cannot be measured. It is apparent, however, from the linear nature of the curves that the

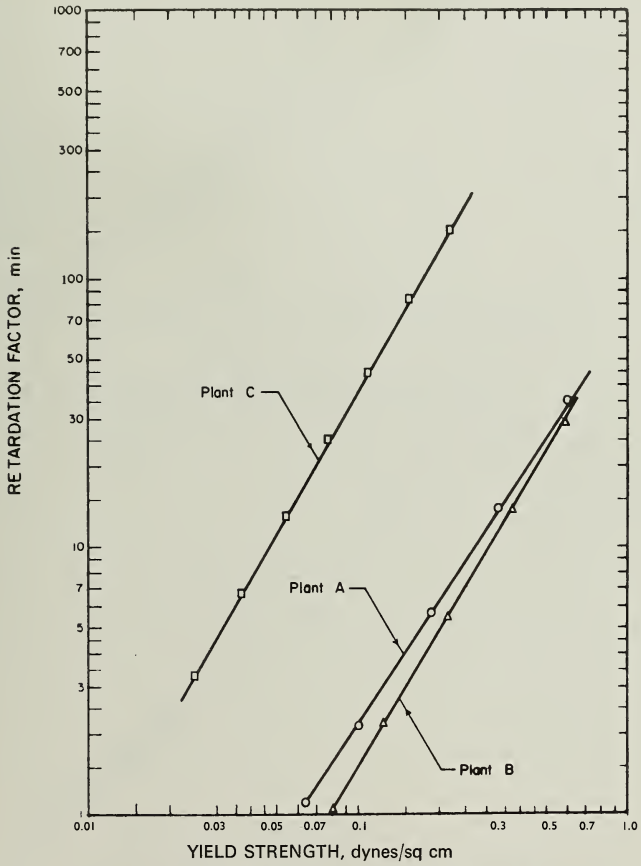

Fig. 7. Relationship between retardation factor and yield strength

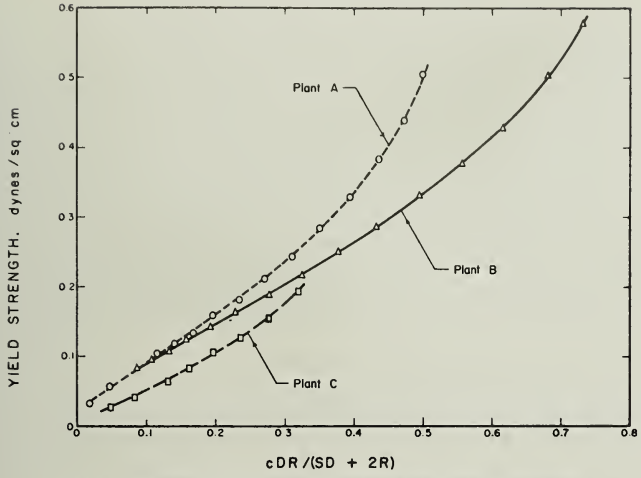

FIG. 8. Relationship between observed yield strength and relative magnitude of structural support—laminar model

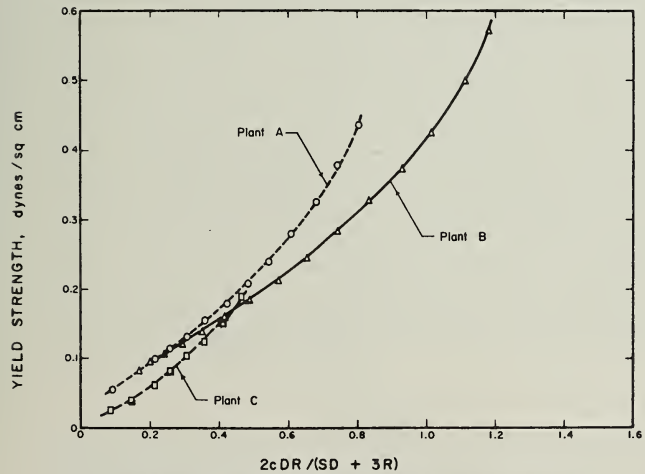

FIG. 9. Relationship between observed yield strength and relative magnitude of structural support—turbulent model

relative magnitude of the structural support force computed from observed settling data is in basic agreement with the measured yield strength.

The upper portion of the curves in Figs. 8 and 9 (corresponding to higher suspended solids concentrations) is not straight. In computing the relative magnitude of τ_{ij} from settling data using equations (18) and (19), the value of D was arbitrarily taken as 1.22 m (4 ft)—the approximate mean of the settling depths observed experimentally. Because the defect in the model manifested itself at high degrees of retardation (Fig. 6), the effect of this assumption was to reduce the computed structural support force at high suspended solids concentrations but to leave it relatively unaffected at low concentrations. Thus the nonlinear portion of the curves in Figs. 8 and 9 was expected.

It will be recalled that the postulated model of sedimentation was something intermediate between the two versions of the mathematical model. The basic correlation between yield strength and observed settling characteristics exists for both the laminar (Fig. 8) and turbulent (Fig. 9) versions of the model. This is not to imply that both versions of the model are correct, but that either is plausible.

SUMMARY AND CONCLUSIONS

The settling characteristics of activated sludge differ from those of the ideal suspension on which gravity thickening theories are based. In this study, the "non-ideal" behavior of activated sludge was interpreted in terms of the rheological properties of the suspension.

A conceptual model of the hypothesized mechanism of subsidence of activated sludge was developed based on an analysis of forces acting on a mass of sludge. The resulting mathematical expression was inconsistent with prevailing theories of thickening, but was in close agreement with the observed settling behavior of activated sludge.

The relative magnitude of the interparticle force, as computed from laboratory settling data by use of the mathematical models was shown to be related to the yield strength of the same sludge as measured with a viscometer. It is concluded that the reason activated sludge fails to conform to prevailing theories of thickening is that it has a yield strength at ordinary mixed liquor suspended solids concentrations. This existence of interparticle forces causes a reduction in settling velocity which is not considered in present theories relating to the area requirement for thickeners.

Contrary to prevailing thickening theories, the area of the thickening portion of a settling basin need not be considered to be inalterably established by the settling velocity of the rate-limiting concentration of activated sludge. The area can be reduced, or the capacity of an existing basin can be increased, by minimizing the reduction in settling velocity due to interparticle forces within the sludge. This can be done physically by controlling the depth and mixing conditions in the settling basin, or it can be done biologically by altering conditions in the activated sludge process to minimize the yield strength of the sludge.

REFERENCES

Behn, V. C. (1957) Settling behavior of waste suspensions, *J. Sanit. Engng. Div. Am. Soc. Civ. Engrs*, **83**, SA5, 1–20.

Coe, H. S. and Clevenger, G. H. (1916) Methods for determining the capacities of slime settling tanks, *Trans. Am. Inst. Min. Engrs*, **55**, 356–84.

Dick, R. I. and Ewing, B. B. (1967a) The rheology of activated sludge, *J. Wat. Pollut. Control Fed* **39**, 543–60.

Dick, R. I. and Ewing, B. B. (1967b) Evaluation of activated sludge thickening theories, *J. Sanit. Engng. Div. Am. Soc. civ. Engrs*, **93**, SA4, 9–29.

Fitch, B. (1962) Sedimentation process fundamentals, *Trans. Am. Inst. Min. Engrs*, **223**, 129–37.

Frank, H. S. and Evans, M. W. (1945) Free volume and entropy in condensed systems, *J. Chem. Phys.* **13**, 507–32.

Kynch, G. J. (1952) A theory of sedimentation, *Trans. Faraday Soc.* **48**, 166–76.

Roberts, E. J. (1949) Thickening—art of science? *Min. Engng*, **1**, 61–64.

Schneebeli, G. (1955) Expériences sur la limite de validité de la loi de Darcy et l'apparition de la turbulence dans en écoulement de filtration, *Houille blanche*, **10**, 141–9.

Shannon, P. T., Dehaas, R. D., Stroupe, E. P. and Tory, E. M. (1964) Batch and continuous thickening, *Ind. Engng Chem. Fundamentals*, **3**, 250–60.

Vand, V. (1948) Viscosity of solutions and suspensions, *J. Phys. Colloid Chem.* **52**, 277–321.

APPENDIX IV

AGGREGATE SIZE VARIATIONS DURING THICKENING OF ACTIVATED SLUDGE

by

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and
Richard I. Dick

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AGGREGATE SIZE VARIATIONS DURING THICKENING OF ACTIVATED SLUDGE

Ali R. Javaheri and Richard I. Dick

A significant improvement in the performance of the activated sludge process could be realized by an increase in the effectiveness of the solids separation and concentration phases of the process. The concentration of mixed liquor suspended solids which can be maintained in aeration tanks and the required size of aeration tanks are dependent directly on the concentration at which sludge solids are returned from the final settling tank. Also, the cost of disposing of waste solids produced in the activated sludge process may be minimized if the difficulty of concentrating the solids into a small volume can be eliminated. While gravity thickening in final tanks or separate thickeners is the most economical way of effecting major reductions in sludge volumes, the effectiveness of thickening has been limited because of the resistance of activated sludge to consolidate to high concentrations. Knowledge of the variation of some basic physical parameters which take place during subsidence of activated sludge would be useful in developing methods for improving thickening.

The purpose of this study was to investigate the fundamental physical behavior of activated sludge during thickening. Specifically, the nature of aggregate size variation and liquid displacement from within the aggregates during thickening has been evaluated. In this study, activated sludge solids are envisioned to be organized physically at three different levels—primary particles, flocs, and aggregates. The assumption is in accordance with Wold's (1) theoretical analysis of the flocculation and with Michaels' and Bolger's (2) experimental findings. The primary particles in sludge such as microorganisms are considered to agglomerate into "floc" particles which serve as the basic building units for further growth of sludge solids. As flocs cluster together, they form "aggregates." The term "floc" includes the solids and liquid within floc particles and the term "aggregate" includes the constituent floc particles as well as the liquid between them. The "porosity" of the suspension is contributed by the interstices between the aggregates.

In this investigation the water content and size of activated sludge aggregates have been analyzed by use of the equation for interface subsidence velocity of concentrated suspensions developed by Richardson and Zaki (3). The water content of aggregates also has been analyzed according to the equation for flow through porous media developed by Carmen and Kozeny (4). An appreciable decrease in aggregate size along with a significant decrease in the water content has been found to accompany thickening. These changes are interpreted to be brought about by two mechanisms, "squeeze" and "split." "Squeeze" refers to the process of squeezing an aggregate to reduce its water content (but not its solids con-

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tent). "Split" refers to the process of splitting an aggregate to smaller sized aggregates, each of which contains only a portion of the water and solids from the original aggregate. When both mechanisms exist, the aggregates become more numerous, smaller, and denser, and they contain less solids than the original aggregates. The prevalence of the squeeze mechanism has been analyzed for activated sludges with widely differing settling characteristics from three different wastewater treatment plants.

To explain aggregate size variation in a different manner, two flow patterns have been defined. One type is interaggregate flow (flow between the aggregates) and the other is intraaggregate flow (flow through the aggregates and between flocs in the aggregate).

Theory and Methods

Richardson—Zaki Equation

Stokes (5) found the terminal velocity, V_0, of a single spherical particle in an infinite fluid under laminar flow conditions to be:

$$V_0 = \frac{g(\rho_m - \rho_w)d^2}{18\mu_w} \quad \ldots\ldots 1$$

where,

d = diameter of the spherical particle,
ρ_m = density of the particle,
ρ_w = density of the liquid,
μ_w = absolute viscosity of the liquid, and
g = gravitational constant.

Stokes' equation is not an adequate description of the settling velocity of particles in concentrated suspensions where particle subsidence is hindered by the presence of neighboring particles.

Richardson and Zaki (3), who studied the subsidence of the interface of a suspension comprised of uniformly sized particles by dimensional analysis, showed that:

$$\frac{V_c}{V_0} = f\left(\frac{V_0 d\rho_m}{\mu_w}, \frac{d}{D}, \epsilon\right) \quad \ldots\ldots 2$$

where,

V_c = suspension interface subsidence velocity,
$\frac{V_0 d\rho_m}{\mu_w}$ = Reynolds number,
D = diameter of settling column, and
ϵ = suspension porosity.

Equation 2 is a general expression which is applicable regardless of the nature of flow about particles. They showed that for wholly viscous flow and for fully developed turbulent conditions, $\frac{V_c}{V_0}$ was independent of Reynolds number, or:

$$\frac{V_c}{V_0} = f\left(\frac{d}{D}, \epsilon\right) \quad \ldots\ldots 3$$

Experimentally, Richardson and Zaki found that subsidence of suspensions of uniformly sized particles could be described by:

$$\frac{V_c}{V_0} = \epsilon^n \quad \ldots\ldots 4$$

Note that the suspension interface velocity at a porosity, ϵ, of 1.0 equals the individual particle settling velocity in an infinite fluid. Comparison of Equations 3 and 4 shows that n is a function only of $\frac{d}{D}$. They used experimental data to relate n and $\frac{d}{D}$. Where Reynolds number was less than 0.2, the relationship was:

$$n = 4.65 + 19.5\frac{d}{D} \quad \ldots\ldots 5$$

The value of n decreased to a constant value of 2.39 at Reynolds numbers greater than 500. The variation of n with intermediate Reynolds numbers is illustrated by Richardson's and Zaki's experimental data (Figure 1).

Richardson's and Zaki's work can be applied to the sedimentation of a suspension of activated sludge aggregates of effective diameter, d, in the following way. Assuming laminar flow and

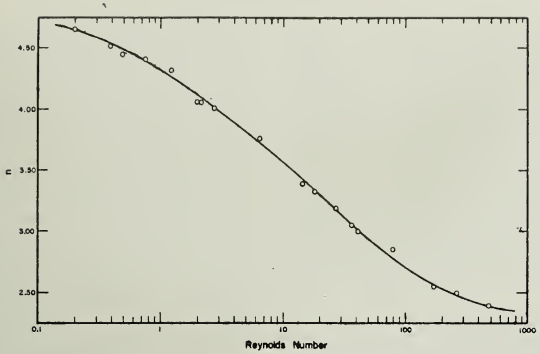

FIGURE 1.—The variation of n $\left(\frac{d}{D} \rightarrow 0\right)$ with intermediate Reynolds numbers is illustrated by Richardson's and Zaki's (3) experimental data.

ignoring the wall effect, Equation 4 can be written as:

$$\frac{V_c}{V_0} = (1 - \Phi_a)^{4.65} \ldots\ldots\ldots 6$$

where Φ_a is the volumetric aggregate concentration. The settling velocity of an aggregate, V_0, can be expressed by Stokes' Law as:

$$V_0 = \frac{g(\rho_a - \rho_w)\bar{d}^2}{18\mu_w} \ldots\ldots\ldots 7$$

where ρ_a is the mass density of aggregates. The value of ρ_a is a quantity which cannot be measured readily; but by means of material balance, its value can be computed. Assuming a unit volume of suspension:

Suspension wt. = wt. dry solids + wt. liquid

Suspension wt. = aggregate wt. + remaining liquid wt.

or;

$$(\rho_s)(1) = \Phi_k(\rho_k) + (1 - \Phi_k)(\rho_w)$$

$$(\rho_s)(1) = \Phi_a(\rho_a) + (1 - \Phi_a)(\rho_w) \ldots 8$$

where,

ρ_s = density of the suspension,
Φ_k = volumetric solids concentration, and
ρ_k = density of the solids.

Equation 8 can be simplified to

$$(\rho_s - \rho_w) = \Phi_a(\rho_a - \rho_w) = \Phi_k(\rho_k - \rho_w) \ldots 9$$

or;

$$(\rho_a - \rho_w) = \frac{\Phi_k}{\Phi_a}(\rho_k - \rho_w) = \frac{1}{A}(\rho_k - \rho_w) \ldots 10$$

where A is the ratio of the volume of aggregates to the volume of dry solids, $\frac{\Phi_a}{\Phi_k}$. Hence, A is a measure of the amount of water associated with solids in aggregates, and it will be referred to as the "Aggregate Volume Index," AVI. Thus

$$\Phi_a = A\Phi_k \ldots\ldots\ldots 11$$

Substitution of Equations 7, 10, and 11 into Equation 6 gives:

$$V_c = \left[\frac{g}{18} \cdot \frac{(\rho_k - \rho_w)\bar{d}^2}{\mu_w A}\right](1 - A\Phi_k)^{4.65} \ldots 12$$

which can be written as:

$$V_c^{1/4.65} = V_0^{1/4.65}(1 - A\Phi_k) \ldots 13$$

or;

$$V_c^{1/4.65} = V_0^{1/4.65} - (V_0^{1/4.65}A)\Phi_k \ldots 14$$

The value of the interface subsidence velocity at any specified concentration, V_c, can be obtained from laboratory batch settling tests. The value of Φ_k, the volumetric solids concentration, can be determined by use of pycnometers. A plot of $V_c^{1/4.65}$ vs. Φ_k then can be made. If the plot is a straight line, the slope of the line will be $[V_c^{1/4.65}A]$ and the ordinate intercept (at $\Phi_k = 0$) will be $V_0^{1/4.65}$. If the aggregate settling velocity and aggregate volume index change with concentration, the plot will be curved. In this case, values of V_0 and A at any concentration can be determined in a similar fashion by use of the tangent to the curve at that concentration. In either event, the equivalent aggregate diameter, d, can be found from the calculated value of V_0 by use of Equation 12.

Hence it is seen that Richardson's and Zaki's work provides a convenient basis for investigating the fundamental changes which occur during thickening of activated sludge. Application of Richardson's and Zaki's equation, however, is based on a number of assumptions, and it is well to review them and their significance. In taking the value of n in Equation 4 to be 4.65, the Reynolds number was assumed to be less than 0.2, and Richardson's and Zaki's correction for the influence of the wall of the settling column was ignored. Based on analysis of the experimentally determined values of the size and settling velocity of individual aggregates, the maximum Reynolds number in the present work was approximately 4.0. From Figure 1, the corresponding value of n also would be about 4.0. An error of opposite sign was introduced by not considering the $19.5\ d/D$ term in Equation 5. Based on the column size used and the largest aggregate diameter encountered, the maximum error in n resulting from this simplification was approximately 10 percent. The accuracy of the selected value of n also was influenced by the assumption that aggregates were spherical in shape. Maude and Whitmore (6) found the value of n to be 5.85 for cubes and 4.14 for discs. In the absence of knowledge of aggregate shape, Krone (7) assumed the value of n for activated sludge to be 5. Hence, it is seen that selection of the value of n as 4.65 was somewhat arbitrary. However, the range of expected variation of n about the value of 4.65 was not considered to be sufficient to influence seriously quantitative results. The general conclusions of the study, it is felt, are not limited by the assumptions relating to selection of the value of n.

In applying Stokes' law to the sedimentation of individual aggregates, the effect of aggregate shape was ignored. Consequently, the computed aggregate diameter, d, was actually the diameter of a hydraulically equivalent sphere. The error in applying Stokes' law in situations where Reynolds number was as high as 4.0 was not significant.

In using Richardson's and Zaki's equation, it is tacitly assumed that only fluid forces control the subsidence of the suspension. That is, activated sludge is assumed to be an ideal suspension for which interface subsidence velocity is only a function of solids concentration (8). Activated sludge is not an ideal suspension because interparticle forces as well as fluid forces resist subsidence (9). The extent to which interparticle forces influence settling velocity can be minimized by use of deep initial settling depth. Dick and Ewing (9) found that the interface subsidence velocity for initial sludge depths of 3.5 ft (1.07 m), such as used in this study, could vary from 40 to 95 percent of the ideal settling velocity, depending on the nature and concentration of the activated sludge. Hence, quantitative determinations based on application of the Richardson-Zaki equation to observed activated sludge settling behavior are subject to error because of the non-ideal settling characteristics of the sludge. However, again, the error is not considered sufficient to invalidate the basic conclusions drawn

from application of Richardson's and Zaki's work.

A final assumption is that the zone settling velocities observed in batch settling tests conducted at various initial solids concentrations are the same as the settling velocities of the suspension at corresponding concentrations produced during the course of thickening. Talmage and Fitch (10) showed that, for ideal suspensions, this assumption is valid; and Shannon *et al.* (11) experimentally confirmed the validity of the assumption by use of a suspension of glass beads. However, Shannon and Torey (12), Hassett (13), and Fitch (14) have reported that the settling velocity of flocculent suspensions depends on the conditions under which the aggregates were formed. That is, aggregates formed by agglomeration of a suspension at a specific initial concentration, C_i, may be different than the aggregates formed when a dilute suspension with an initial concentration less than C_i thickens to the concentration C_i. Again, this assumption is felt to limit the exactness of the quantitative data but not the conclusions reached by application of the Richardson and Zaki analysis.

Carmen—Kozeny Equation

Carmen (4) demonstrated that, for a porous bed composed of spherical uniform particles of diameter d, the superficial velocity, u, of liquid through the bed can be expressed as:

$$u = \frac{d^2}{K} \frac{\epsilon^3}{36\mu_w(1-\epsilon)^2} \frac{\Delta p}{L} \quad \ldots\ldots 15$$

where,

K = constant,
Δp = pressure difference across length of bed, and
L = length of porous bed.

Carmen felt that K could be taken as a constant with an average value of 5.0. Coulson (15), however, noted that K varied between 3.2 and 5 depending on factors such as particle shape. Analysis of the data used by Scott (16) indicates an even wider variation in the value of K. Scott applied the Carmen-Kozeny equation (Equation 15) to sedimentation data for kaolinite clay and assumed K to be a constant of unknown value. The same assumption was made in this study.

In applying Equation 15 to batch sedimentation of activated sludge, aggregates replace the spherical solid particles, and the interstices between the aggregates contribute the porosity of the suspension. The superficial upward velocity of liquid, u, is equal to the interface subsidence velocity, V_c. The pressure drop per unit length is also equal to the net weight of solids supported by the unit height of the suspension, or:

$$\frac{\Delta p}{L} = (1-\epsilon)(\rho_a - \rho_w)g \quad \ldots\ldots 16$$

Substitution of Equation 16 into Equation 15, and considering $u = V_c$:

$$V_c = \frac{g(\rho_a - \rho_w)d^2}{36K\mu_w} \frac{\epsilon^3}{1-\epsilon} \quad \ldots\ldots 17$$

since;

$$\epsilon = 1 - \Phi_a = 1 - A\Phi_k \quad \ldots\ldots 18$$

and;

$$(\rho_a - \rho_w) = \frac{1}{A}(\rho_k - \rho_w) \quad \ldots\ldots 19$$

Equation 17 can be written as:

$$V_c = \left[\frac{g(\rho_k - \rho_w)d^2}{36K\mu_w A^2}\right] \frac{(1-A\Phi_k)^3}{\Phi_k} \quad \ldots 20$$

Substituting K_1 for the bracketed term in Equation 20:

$$(V_c\Phi_k)^{\frac{1}{3}} = K_1^{\frac{1}{3}}(1 - A\Phi_k) \quad \ldots\ldots 21$$

or;

$$(V_c\Phi_k)^{\frac{1}{3}} = K_1^{\frac{1}{3}} - (K_1^{\frac{1}{3}}A)\Phi_k \quad \ldots 22$$

As explained previously, the values of V_c and Φ_k were obtained experimentally for the suspensions of activated sludge. To apply the Carmen-Kozeny equation, then, $(V_c\Phi_k)^{\frac{1}{3}}$ was plotted as a function of Φ_k. From the slope of the plot obtained at any specified concentration,

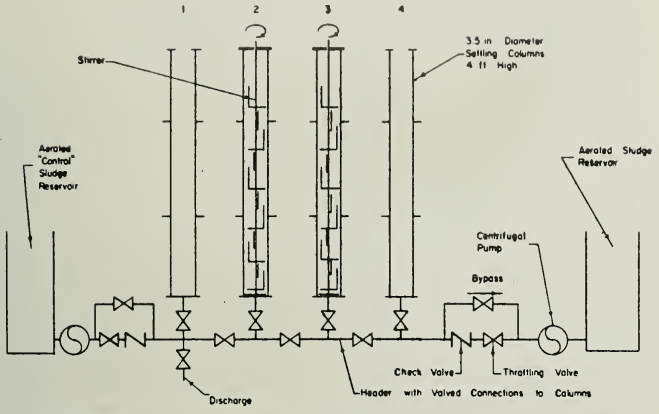

FIGURE 2.—The settling tests were conducted in 4 3.5-in. (8.9-cm) diam columns. (Note: Ft × 0.3 = m.)

the value of aggregate volume index A and K_1 could be calculated. Since the value of K (Equation 20) was unknown, the equivalent aggregate diameter, $\bar{d}$, could not be determined.

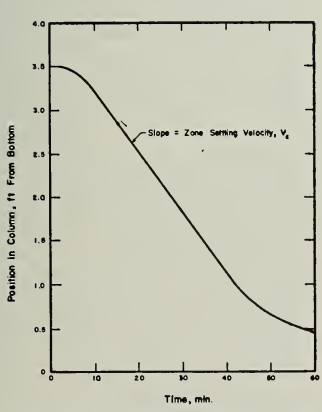

FIGURE 3.—Subsidence of the sludge interface is observed on this typical batch settling curve. (Note: Ft × 0.3 = m.)

Laboratory Procedure

Batch settling tests to determine the sludge interface subsidence velocities were made with activated sludge samples taken from three different activated sludge wastewater treatment plants. Plant I was a municipal treatment plant using the conventional activated sludge process. The normal sludge settling behavior at Plant I was very satisfactory. Plant II was a municipal wastewater treatment plant using the Kraus and contact stabilization modifications of the activated sludge process. The samples were collected from the contact tanks. Settling behavior at Plant II also was satisfactory. Plant III was a small municipal contact stabilization plant treating an appreciable amount of carbohydrate waste discharged by industry. The settling behavior of this sludge was very poor.

The settling tests were conducted at a temperature of 20° ± 2°C using the apparatus shown in Figure 2. It consisted of 4 3.5-in. (8.9-cm) diam columns, reservoirs, pumps, and a piping system. The sludge was pumped

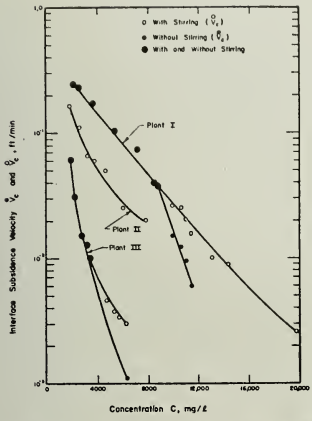

FIGURE 4.—The three activated sludge plants had different interface subsidence velocities. (Note: Ft × 0.3 = m.)

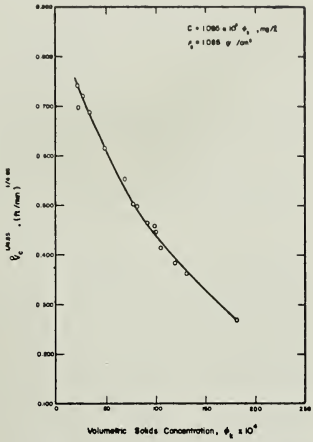

FIGURE 5.—Application of Richardson's and Zaki's equation to sedimentation of activated sludge from Plant I. (Note: Ft × 0.3 = m.)

to a height of 3.5 ft (1.07 m) in the columns at a predetermined rate to insure homogeneous distribution of solids. Subsidence of the sludge interface then was observed (Figure 3). It is characterized by an initial period with little subsidence followed by a period of settling at a constant rate. The slope of the linear part of the settling curve was the interface settling velocity, V_c, for the sludge at its initial concentration.

Slow stirring was provided to promote agglomeration and to minimize the bridging which occurs in laboratory settling columns when high concentrations of activated sludge are used. A comparison of results obtained by analyzing settling data with and without stirring by use of the Richardson-Zaki equation afforded a measure of the effect of stirring. It should be noted, however, that Vesilind (17) has found that the beneficial effect of stirring is to minimize the artificial effects created in laboratory settling columns. Hence, data from the stirred columns are considered to be more indicative of thick-

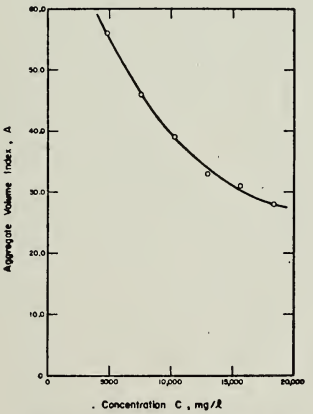

FIGURE 6.—The aggregate volume index, A, was obtained by drawing tangents to the curve (Figure 5) at selected concentrations and solving for the equations of the tangent lines. (Plant I shown.)

ening as it actually occurs in full scale settling basins. Small stirrers rotated at 1 rpm were constructed from 0.125-in. (3.18-mm) diam aluminum bars (Figure 2). Thirteen angles, 3 in. × 3 in. (7.62 cm × 7.62 cm) in size, here were welded on 3-in. (7.62-cm) centers at the midpoint of one leg to the main vertical bar.

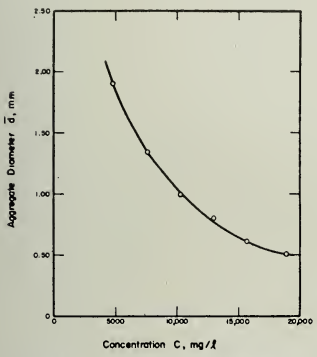

FIGURE 7.—The equivalent aggregate diameter, $\bar{d}$, was calculated by use of Equation 12. (Plant I shown.)

The volumetric concentration of solids, Φ_k, and solids density, ρ_k, were determined at 20°C by use of 50-ml pycnometers. The volumetric and gravimetric concentrations of a specific sludge were directly proportional because the density of the solids remained constant.

The relationship between suspended solids concentration and interface settling velocity for activated sludge from Plants I, II, and III is shown in Figure 4. Significant differences between the settling characteristics of the three activated sludges may be noted. The concentration ranges for the three sludges were appreciably different because of variations in sludge characteristics caused by the particular operating conditions in the three plants. The concentration range used for each

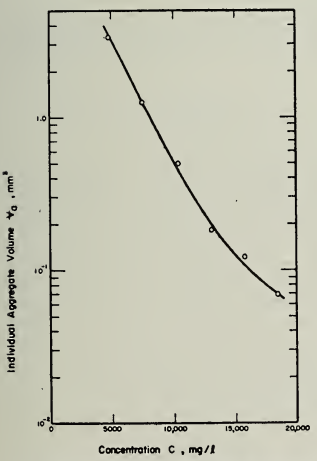

FIGURE 8.—As the concentration increased, the individual aggregate volume decreased. (Plant I shown.)

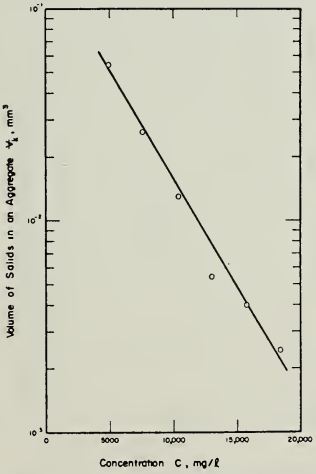

FIGURE 9.—The volume of solids in each aggregate decreased as the concentration increased. (Plant I shown.)

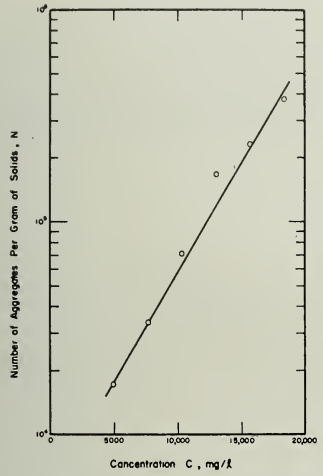

FIGURE 10.—The number of aggregates increased rapidly as the concentration increased. (Plant I shown.)

sludge was considered to represent the thickening conditions which could exist in the respective plants.

Application of Richardson's and Zaki's Equation

The settling data shown in Figure 4 were analyzed by use of the Richardson-Zaki equation. Results for the stirred samples of sludge from Plant I are presented here in detail. Results for Plant II are summarized briefly in the text. Results for both the stirred and unstirred samples from Plant III are pre sented to illustrate the typical effect of mixing. Figure 5, a plot of $\mathring{V}_c^{1/4.65}$ vs. the volumetric solids concentration, Φ_k, for sludge from Plant I, establishes the relationship between Φ_k and the gravimetric concentration, C, as determined by use of pycnometers. The fact that the curve in Figure 5 is not linear indicates (Equation 14) that the settling velocity of an individual aggregate, V_0, and the aggregate volume index, A, changed with concentration. Values of A and V_0 were obtained by drawing tangents to the curves at selected concentrations and solving for the equations of the tangent lines according to Equation 14. From the

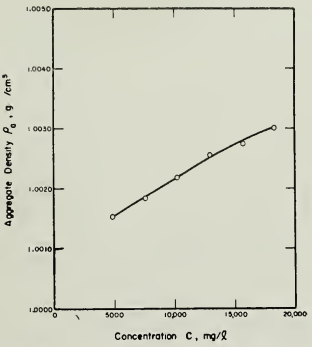

FIGURE 11.—The aggregate density was calculated from Equation 10. (Plant I shown.)

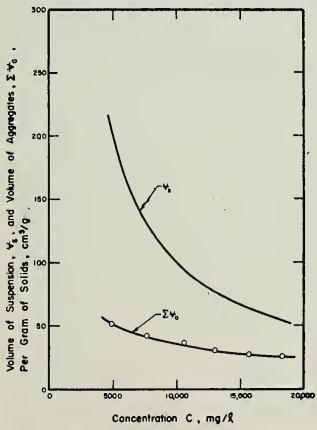

FIGURE 12.—The amount of water between aggregates can be computed by comparing suspension and aggregate volumes. (Plant I shown.)

values of V_0 obtained, the equivalent aggregate diameter, d, was calculated at various concentrations by use of Equation 12 (Figures 6 and 7). The figures show that in concentrating from 5,000 mg/l to 19,000 mg/l, the diameter of aggregates was reduced from approximately 1.9 mm to 0.5 mm, and the ratio of the volume of water associated with each volume of solids was reduced from 56 to 28.

From these data it was possible to compute the number of aggregates which existed at any concentration, as

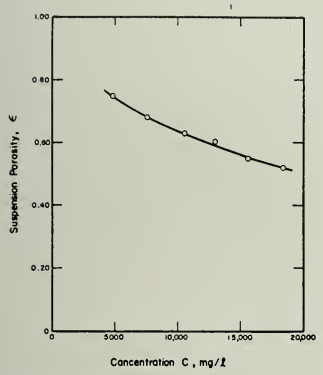

FIGURE 13.—Porosity decreased 28 percent as the sludge from Plant I thickened from 5,000 mg/l to 19,000 mg/l.

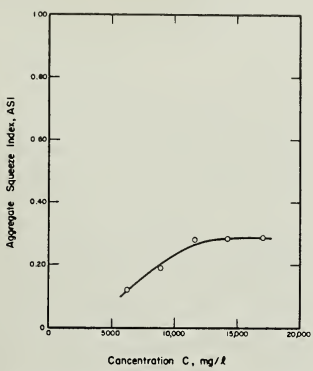

FIGURE 15.—The aggregate squeeze index indicates the fraction of clarified liquid which originated from within aggregates as thickening took place. (Plant I shown.)

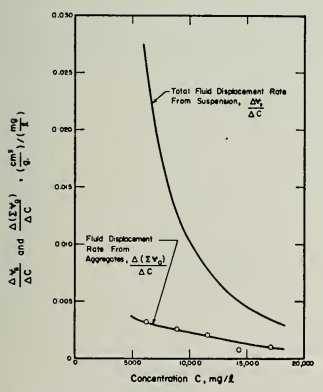

FIGURE 14.—Fluid displacement rates varied with concentration. (Plant I shown.)

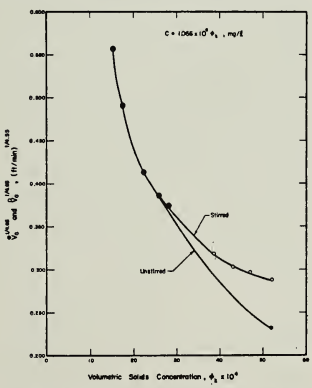

FIGURE 16.—Richardson's and Zaki's equation was applied to the sedimentation of activated sludge from Plant III.

well as their volume and density. Also, the volume and weight of actual solids in each aggregate could be calculated as could the porosity of the suspension at any concentration. Figures 8 and 9 indicate the decrease in individual aggregate volume, $\forall_a$, and the volume of actual solids in each aggregate, $\forall_k$, which occurred as concentration increased. As the concentration of the suspension increased, the number of aggregates, N, increased rapidly (Figure 10). Figure 11 shows the increase in the aggregate density, ρ_a, as calculated from Equation 10, which accompanied an increase in concentration.

The difference between the curves for the total volume of suspension, $\forall_s$, and the total volume of aggregates per gram of suspension, $\Sigma \forall_a$, represents the amount of water between aggregates (Figure 12). The porosity, ϵ, at any concentration is given by $\frac{\forall_s - \Sigma \forall_a}{\forall_s}$. The relationship between porosity and concentration (Figure 13) indicates that porosity decreased from 70 percent to 50 percent as the sludge from Plant I thickened from 5,000 mg/l to 19,000 mg/l.

It is of interest to know whether the volume reduction which accompanies thickening at any particular concentration is caused by elimination of water

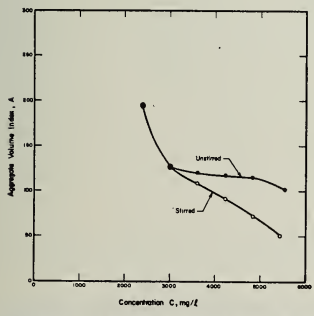

FIGURE 17.—Aggregate volume index varied with solids concentration. (Plant III shown.)

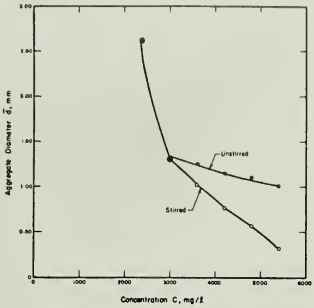

FIGURE 18.—As concentration increased, the aggregate diameter decreased. (Plant III shown.)

from between aggregates or by squeezing of water from within aggregates. Figure 14 shows the rate of change of suspension volume, $\forall_s$, and total aggregate volume, $\Sigma \forall_a$, with respect to concentration as given by the slopes of the curves in Figure 12. To give a measure of the significance of particle squeeze during thickening, the quantity $\frac{\Delta(\Sigma \forall_a)}{\Delta \forall_s}$ is defined as the "Aggregate Squeeze Index," ASI. The ASI indicates the fraction of clarified liquid which originated from within aggregates as thickening took place. ASI would be 0 for incompressible aggregates and would achieve a maximum value of 1.0 when all displaced fluid originated from within aggregates. For the sludge from Plant I, 15 percent of the total water being displaced from the consolidating sludge mass was coming from inside aggregates when the suspended solids concentration was 7,000 mg/l (Figure 15). This fraction doubled by the time the sludge concentration reached 15,000 mg/l.

Figures 8, 9, 10, and 11 show that as thickening took place, the activated sludge aggregates became smaller, contained less solids than the initial aggregates, increased in number, and experienced an increase in density. It is suggested that these phenomena were

brought about by the two physical mechanisms, "squeeze" and "split," as defined previously. By the process of squeezing, the water content of activated sludge aggregates is reduced. By the process of splitting, an aggregate is divided into smaller aggregates, but no water is removed. Both the water content and solids content of an aggregate become divided by "split." The experimental results show that both mechanisms prevailed during thickening of the activated sludge from Plant I because the aggregates became smaller, denser, and they increased rapidly in number.

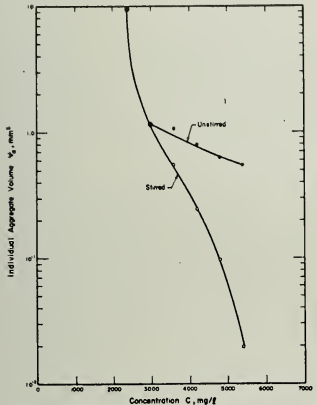

FIGURE 19.—At a given concentration, the aggregates of a stirred sample were smaller than those of the unstirred sample. (Plant III shown.)

To explain the changes which take place during thickening in a different manner, two different flow patterns may be considered (16). Some of the liquid originating from the body of aggregates and from the interstices between aggregates is displaced from the subsiding sludge mass by "interaggregate flow" or flow between aggregates. Some of the liquid, however, is displaced by flowing through aggregates, and this can be termed "intraaggregate flow." In applying Richardson's and Zaki's equation to settling data, the manifestation of intraaggregate flow is a reduction of the apparent size of the basic settling units or aggregates.

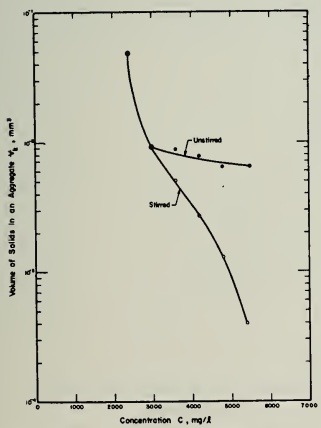

FIGURE 20.—The volume of solids in an aggregate decreased with an increase in solids concentration. (Plant III shown.)

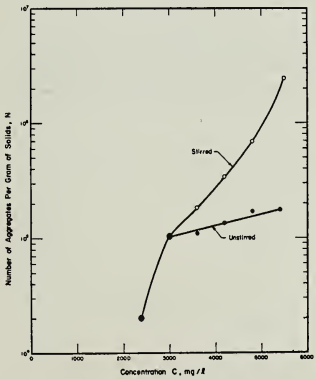

FIGURE 21.—The number of aggregates increased as the solids concentration increased. (Plant III shown.)

Figure 16 shows the application of Richardson's and Zaki's equation to the sedimentation of stirred and unstirred samples of the poorly settling sludge from Plant III. The curvature of Figure 16 again indicates that the aggregate size varied during the thickening process. The decrease in aggregate volume index, A, and aggregate size, d, with increasing concentration is indicated in Figures 17 and 18. Similarly, Figures 19 through 26 are plotted for the sample from Plant III by the methods described previously. Note that considerable differences existed between aggregate characteristics in the stirred and unstirred samples. At a given concentration, the aggregates of a stirred sample were smaller, denser, and larger in number than those of the unstirred sample (Figures 19, 21, and 22). The suspension porosity and the aggregate squeeze index of the stirred sample increased with concentration; while these variables decreased with concentration for unstirred samples (Figures 24 and 26). While it may seem unreasonable that porosity should be greater in slow-settling, highly concentrated suspensions than in more dilute suspensions, it should be noted that

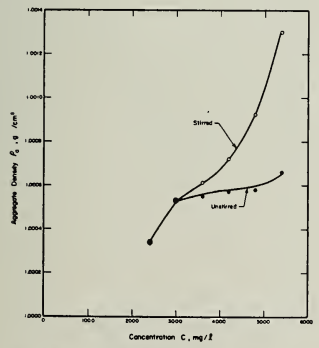

FIGURE 22.—Aggregate density of the stirred samples increased more rapidly than for the unstirred sample with an increase in solids concentration. (Plant III shown.)

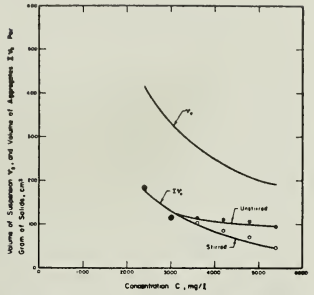

FIGURE 23.—Volume of suspension and aggregate volume for Plant III varied with solids concentration as shown.

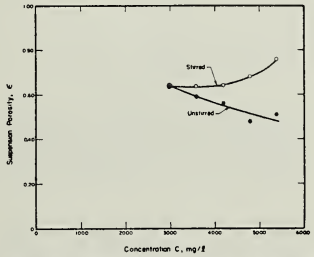

FIGURE 24.—The suspension porosity increased for the stirred samples and decreased for the unstirred samples with an increase in concentration. (Plant III shown.)

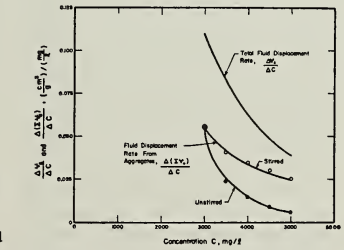

FIGURE 25.—Variation of fluid displacement rates with concentration is shown for Plant III.

the individual aggregate settling velocity, V_0, decreased at higher concentrations and that this change could offset an increase in porosity (Equation 4). Presumably, stirring destroyed bridge networks in the suspension, enhanced squeezing of the aggregates, and produced a greater aggregate squeeze index in the concentrating suspension of activated sludge. As before, both the squeeze and the split mechanisms were prevalent during the thickening of the stirred and the unstirred samples from Plant III.

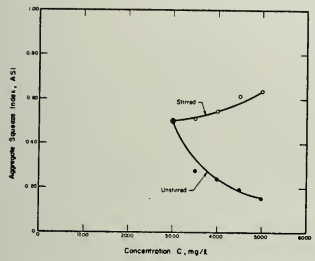

FIGURE 26.—The poor settling sludge from Plant III had a much larger aggregate squeeze index than the better settling sludge from Plant I (Figure 15).

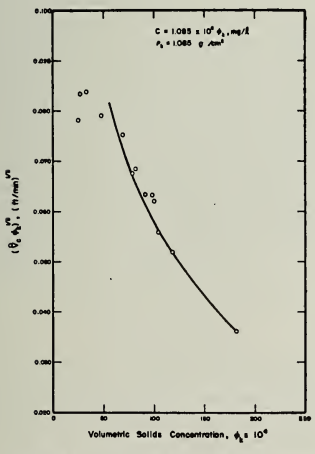

FIGURE 27.—Carmen's and Kozeny's equation can be applied to the sedimentation of activated sludge to determine the aggregate volume index. (Plant I shown.)

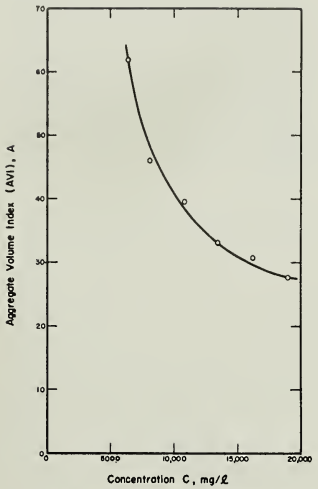

FIGURE 28.—Carmen's and Kozeny's equation for the aggregate volume index yielded results which corresponded closely with those from the Richardson and Zaki equation. (Plant I shown.)

Comparison of results for the stirred samples from Plants I and III indicates several significant points. The poor settling sludge from Plant III had a much larger aggregate squeeze index (Figure 26) than the better settling sludge from Plant I (Figure 15). This means that a large fraction of the fluid clarified from the poor settling sludge originated from the bodies of the aggregates. The poor settling sludge also had a smaller porosity (Figure 24) than the better settling sludge (Figure 13) in the respective concentration ranges of the two sludges. It seems that a good settling sludge is characterized by its high porosity and low aggregate squeeze index (ASI). When sludge character-

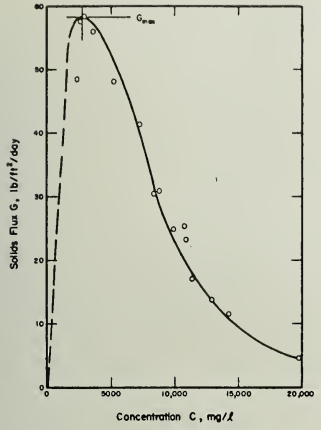

FIGURE 29.—The solids flux curve is used in the analysis of thickening. (Plant I shown.)

istics are such that squeeze of aggregates must be relied on to achieve higher concentrations, thickening does not take place readily.

A similar analysis was carried out for samples from Plant II. For stirred samples from Plant II the nature of variations of AVI and aggregate diameter were comparable to those described for sludge from Plant I. With unstirred samples, a plot of the Richardson-Zaki equation in the form of Equation 14 gave a straight line over the range of concentration from 1,970 to 7,190 mg/l, indicating that the aggregate volume index, A, and aggregate diameter, $\bar{d}$, were constant for this sludge.

Application of Carmen's and Kozeny's Equation

As described previously the values of A (aggregate volume index) and K_1 could be determined by plotting $(V_c\Phi_k)^{\frac{1}{3}}$ vs. Φ_k (Equation 22). Figure 27 shows the plot for the activated sludge sample from Plant I. The decrease in the aggregate volume index, A, with concentration is indicated in Figure 28. The values agreed closely with those obtained by use of Richardson's and Zaki's equation (Figure 6). Since the value of K (Equation 20) was not known, the equivalent aggregate diameter, $\bar{d}$, could not be calculated. This is one of the disadvantages of using the Carmen-Kozeny equation for analysis of settling data.

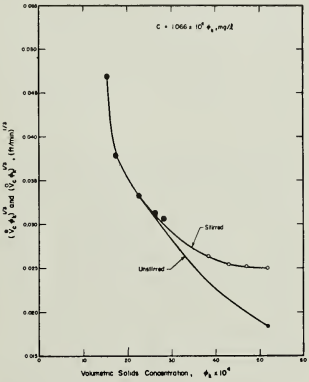

FIGURE 30.—Application of the Carmen-Kozeny equation to the settling data from Plant III is shown.

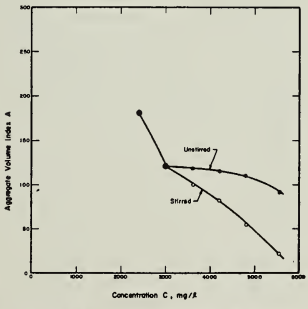

FIGURE 31.—Variation of aggregate volume index with concentration is shown, based on the Carmen-Kozeny equation. (Plant III shown.)

Another disadvantage of the equation is that as Φ_k approaches zero, $(V_c\Phi_k)^{\frac{1}{3}}$ also approaches zero. Note that $V_c\Phi_k$ is proportional directly to solids flux ($G = CV_c$) which is used commonly in analysis of thickening (18)(19). The solids flux curve, G vs. C, has the characteristic shape shown in Figure 29. Now, $(V_c\Phi_k)^{\frac{1}{3}}$ is proportional directly to the cube root of the ordinate values in solids flux curve. If a smooth curve has to be drawn in Figure 27 to apply the Carmen-Kozeny equation, the data should represent the values of G following G_{max}. The Carmen-Kozeny equation cannot be applicable, then, to settling data at concentrations corresponding to solids flux values at the left side of G_{max}. The values omitted from the curve in Figure 27 indicate this point. Application of the Carmen-Kozeny equation to the values only on the right side of G_{max} (Figure 27) can provide an estimate of the aggregate volume index as shown later. The disadvantages mentioned limited the utility of the Carmen-Kozeny equation as a means of aggregate size analysis of activated sludge.

Application of the Carmen-Kozeny equation to the settling data from Plant III is illustrated in Figure 30. The values of the aggregate volume index, A or AVI (Figure 31) compared closely to those obtained by using the Richardson-Zaki equation (Figure 17). Application of the equation to data for the unstirred sample from Plant II again indicated a constant value for the aggregate volume index, A, in the concentration range of 1,970 to 7,190 mg/l; and analysis of the Plant II stirred data indicated that the aggregate volume index decreased as concentration increased.

The decrease in the aggregate volume index with increasing concentration found by application of the Carmen-Kozeny equation indicated squeezing of the aggregates. Splitting of the aggregates could not be shown by the application of the Carmen-Kozeny equation, since aggregate diameters could not be calculated.

Conclusions

To obtain information regarding the fundamental behavior of activated sludge during thickening, this study was carried out to determine the nature of liquid displacement from aggregate particles and to determine the manner in which aggregate particle size varies as consolidation takes place. Analysis of the experimental data was based primarily on an equation for the reduced settling velocity of a suspension.

The following conclusions may be drawn:

1. As the concentration of activated sludge increases, the aggregates which comprise the sludge are squeezed to eliminate water and are split into smaller aggregates. The combined effect of "squeeze" and "split" is that aggregates become smaller, more numerous, and more dense as thickening takes place.

2. The fluid eliminated from subsiding sludge masses originates from within aggregate particles and from the interstices between aggregates. The "aggregate squeeze index," ASI, has been introduced to describe the role which aggregate "squeeze" plays in thickening. It is the fraction of the total water being eliminated at any particular concentration which is originating from within aggregate particles. Based on the settling characteristics of sludges from the plants studied here, activated sludges with good settling characteristics have low ASI and high porosity values, and thickening to high concentrations occurs primarily by elimination of intersticial water. In contrast, sludges with poor settling properties have high ASI values and low porosities. That is, much of the water removed in the course of thickening of poor settling sludges comes from inside the aggregates.

3. Slow stirring during laboratory settling tests appreciably alters the

settling velocity of high concentrations of activated sludge. The faster settling velocities commonly observed in stirred columns may be caused by the fact that stirring increases the aggregate squeeze index. However, the low ASI values associated with unstirred columns may reflect the bridging in laboratory settling columns and may not be a factor in prototype settling basins.

4. The thickening of activated sludges brings about two flow patterns within the mass of aggregates. Some of the total displaced fluid which originates from the interstices of the suspension and bodies of the aggregates travels between the subsiding aggregates. This is referred to as interaggregate flow. At the same time, some of the fluid travels through the subsiding aggregates. This is referred to as intraaggregate flow. Intraaggregate flow accompanies the split of aggregates to smaller ones.

Acknowledgment

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APPENDIX

Notation

The following symbols are used in this paper:

A = ratio of the aggregate volume to the volume of solids in the aggregate,

ASI = aggregate squeeze index, $\frac{\Delta\Sigma \forall_a}{\Delta \forall_s}$,

AVI = aggregate volume index, same as A,

C = gravimetric solids concentration, (F/L^3),

C_i = initial gravimetric solids concentration, (F/L^3),

d = diameter of the spherical particle, (L),

$\bar{d}$ = equivalent aggregate diameter, (L),

D = diameter of settling column, (L),

g = gravitational constant, (L/T^2),

G = solids flux, (F/L^2T),

G_{max} = maximum solids flux, (F/L^2T),

K = constant of Carmen's and Kozeny's equation,

K_1 = term in bracket in Equation 20,

L = length of porous bed, (L),

N = number of aggregates per unit weight of solids, $\left(\frac{1}{F}\right)$,

n = exponent in Richardson's and Zaki's equation,

Δp = pressure difference, (F/L^2),

u = superficial upward velocity, (L/T),

V_0 = independent settling velocity of an individual aggregate, (L/T),

V_c = suspension interface subsidence velocity, (L/T),

$\mathring{V}_c$ = interface subsidence velocity with stirring, (L/T),

$\mathring{V}_c$ = interface subsidence velocity without stirring, (L/T),

$\forall$ = volume (L^3),

ρ = density (FT^2/L^4),

Φ = volumetric concentration,

μ = absolute viscosity, (FT/L^2), and

ϵ = suspension porosity.

Subscript Notations

a = aggregate,

k = solids,

m = spherical particle,

s = suspension of activated sludge, and

w = liquid.

References

1. Wold, M. J., "Computer Simulation of Floc Formation in a Colloidal Suspension." *Jour. Colloid Sci.*, **18**, 684 (1963).
2. Michaels, A. S., and Bolger, J. C., "The Plastic Flow Behavior of Flocculated Kaolin Suspensions." *Ind. Eng. Chem. Fundamentals*, **1**, 153 (1962).
3. Richardson, J. F., and Zaki, W. N., "Sedimentation and Fluidization. Part I." *Trans. Inst. Chem. Engr.*, **32**, 35 (1954).

4. Carmen, P. C., "Fluid Flow Through Granular Beds." *Trans. Inst. Chem. Engr.*, **15**, 150 (1937).
5. Stokes, G. G., "On the Theories of Internal Friction of Fluids in Motion, and of the Equilibrium and Motion of Elastic Solids." *Trans. Cambridge Phil. Soc.*, **8**, 287 (1845).
6. Maude, A. D., and Whitmore, R. L., "A Generalized Theory of Sedimentation." *Brit. Jour. Appl. Phys.*, **9**, 477 (1958).
7. Krone, R. B., "Discussion of Evaluation of Activated Sludge Thickening Theories by Richard I. Dick and Benjamin B. Ewing," *Jour. San. Eng. Div., Amer. Soc. Civil Engr.*, **94**, SA3, 554 (1968).
8. Kynch, G. J., "A Theory of Sedimentation." *Trans. Faraday Soc.*, **48**, 166 (1952).
9. Dick, R. I., and Ewing, B. B., "Evaluation of Activated Sludge Thickening Theories." *Jour. San. Eng. Div., Proc. Amer. Soc. Civil Engr.*, **93**, SA4, 9 (1967).
10. Talmage, W. P., and Fitch, E. B., "Determining Thickener Unit Areas." *Ind. Eng. Chem.*, **47**, 38 (1955).
11. Shannon, P. T., Dehaas, R. D., Stroupe, E. P., and Tory, E. M., "Batch and Continuous Thickening." *Ind. Eng. Chem. Fundamentals*, **3**, 250 (1964).
12. Shannon, P. T., and Tory, E. M., "Settling of Slurries." *Ind. Eng. Chem.*, **57**, 18 (1965).
13. Hassett, N. J., "Design and Operation of Continuous Thickeners." *Ind. Chemist*, **34**, 489 (1958).
14. Fitch, E. B., "Sedimentation Process Fundamentals." *Trans. Amer. Inst. Mining Eng.*, **223**, 129 (1962).
15. Coulson, M. M., "The Flow of Fluids Through Granular Beds: Effect of Particle Shape and Voids in Streamline Flow." *Trans. Inst. Chem. Engr.*, **27**, 237 (1949).
16. Scott, K. J., "Mathematical Models of Mechanism of Thickening." *Ind. Eng. Chem. Fundamentals*, **5**, 109 (1966).
17. Vesilind, P. A., "The Influence of Stirring in the Thickening of Biological Sludge." Doctoral Thesis, Univ. North Carolina, Chapel Hill, North Carolina (1968).
18. Hasset, N. J., "Concentrations in a Continuous Thickener." *Ind. Chemist*, **40**, 29 (1964).
19. Shannon, P. T., and Tory, E. M., "The Analysis of Continuous Thickening." *Soc. Mining Engr.* **235**, 375 (1966).

APPENDIX V

DISTRIBUTION OF COMPRESSIVE FORCES IN SUBSIDING SLUDGE MASSES

by

Richard I. Dick
and
Byong S. Shin

Summary of Preliminary Results
of Work in Progress

DISTRIBUTION OF COMPRESSIVE FORCES IN SUBSIDING SLUDGE MASSES

In a suspension settling at uniform velocity, the effective weight of the particles is equalled by the forces resisting their subsidence. In a concentrated suspension, these forces may arise from fluid drag and from interparticle contacts with adjacent particles. In order to obtain understanding of the fundamental factors which control subsidence of sludges it is of interest to know the relative significance of the two forms of support under different conditions. The interparticle forces produce compressive stresses in the sludge which can result in elimination of water by compression. The fluid drag forces give rise to excess hydrostatic pressure in the pore water of the settling suspension.

Experimentally, the work was conducted by observing profiles of excess hydrostatic pressure and solids concentration during batch sedimentation tests with sludge from a water softening plant. Tests were conducted in a 3.5 in. diameter, 4-ft deep laboratory settling column. The solids profiles gave a measure of the effective weight of suspended solids above any point at any time and comparison of this value with the measured excess hydrostatic pressure at the same location permitted computation of the amount of solids supported by interparticle forces and hence of the compressive stress within the supporting sludge. Figure 1 shows typical data arising from use of this procedure. It is seen, as expected, that very low compressive stresses exist at the beginning of sedimentation tests but that appreciable stresses are achieved after a period of time. The technique also permits computation of the permeability of the suspension at any point or time. Typical results are shown in Figure 2. As shown by the figure, permeability has been found to be principally a function of concentration, regardless of when or where

that concentration occurs. Note that the suspension permeability changed dramatically with solids concentration. A four-fold increase in concentration resulted in a reduction in permeability by a factor of about 180.

Although the compressive yield strength in confined conditions cannot be computed from measured shear stress on theoretical basis, it is interesting to compare the relative magnitude of the two values. Figure 3 shows the measured compressive yield strength from sedimentation tests as a function of yield stress as measured in a rotational viscometer. The figure illustrates that laboratory measurement of the yield strengths of suspensions could potentially serve to permit evaluation of their potential thickening characteristics.

Although the work on measurement of the relative significance of fluid drag and interparticle forces is still underway, analyses to date indicate that, as expected, the final concentration of solids which can be achieved depends upon the compressibility of a suspension while the rate at which this concentration is reached depends also on suspension permeability. An increase in sludge depth increases final solids concentration because it increases the compressive force on the sludge mass. Low permeability has been shown to have a double effect on thickening. It not only retards the rate of upward egression of water but also reduces the amount of compressive force for sludge consolidation.

The analysis has permitted evaluation of the effect of stirring in laboratory settling columns. Stirring significantly increases the compressibility of a suspension but reduces the permeability and thus retards escape of the water displaced from the subsiding sludge mass.

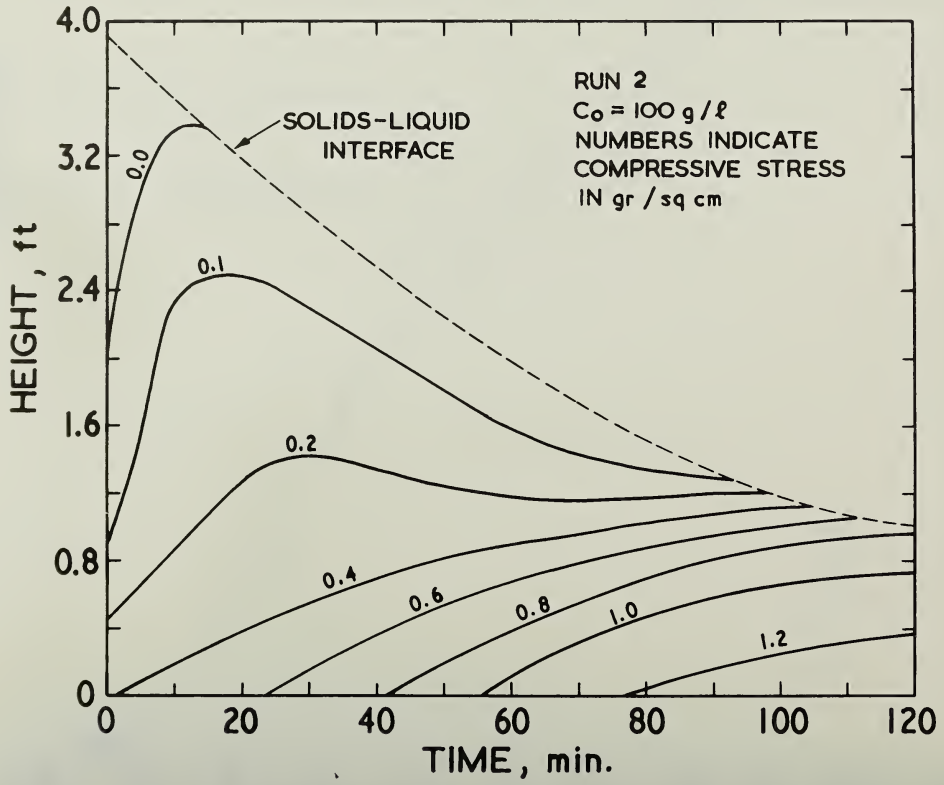

FIGURE 1. DISTRIBUTION OF COMPRESSIVE STRESSES DURING SEDIMENTATION OF WATER TREATMENT PLANT SLUDGE

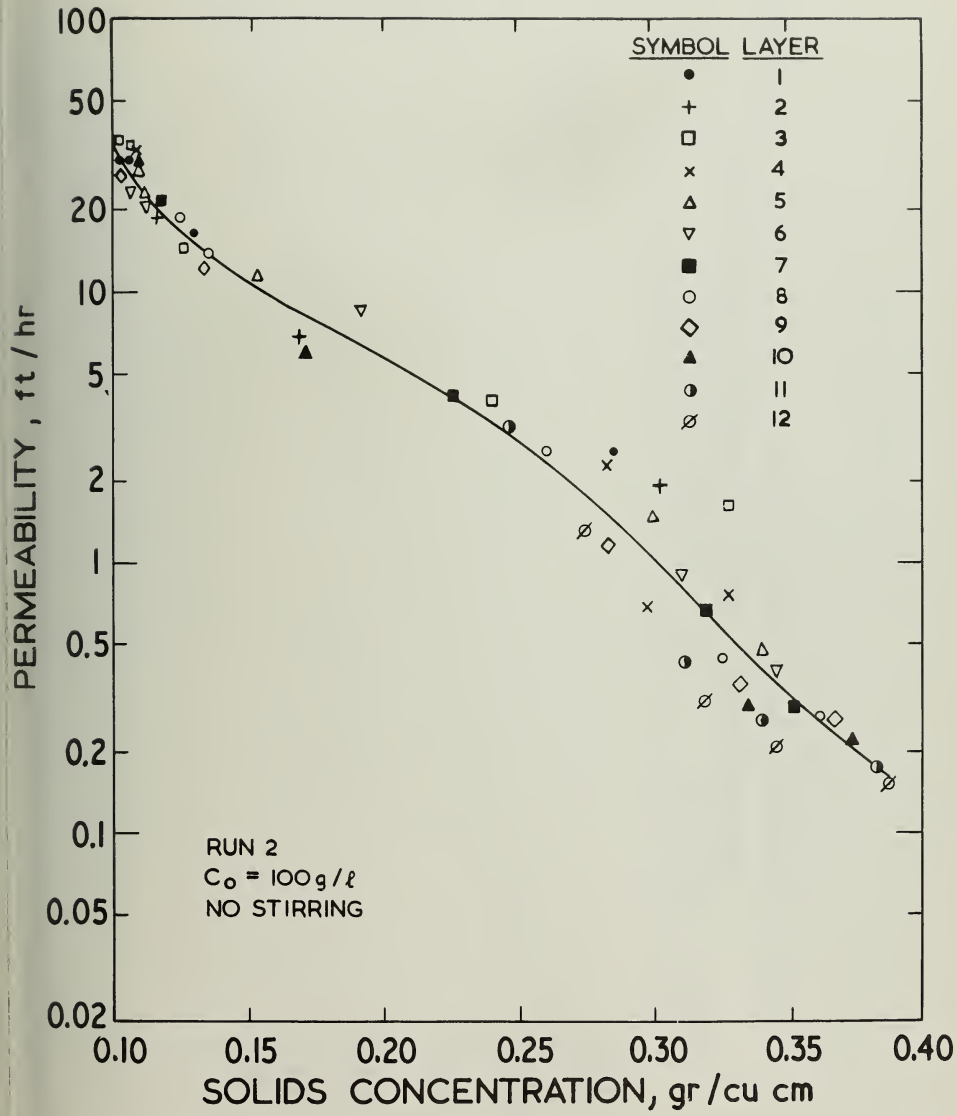

FIGURE 2. CHANGES IN PERMEABILITY OF WATER TREATMENT PLANT SLUDGE AS CONCENTRATION CHANGES DURING SEDIMENTATION

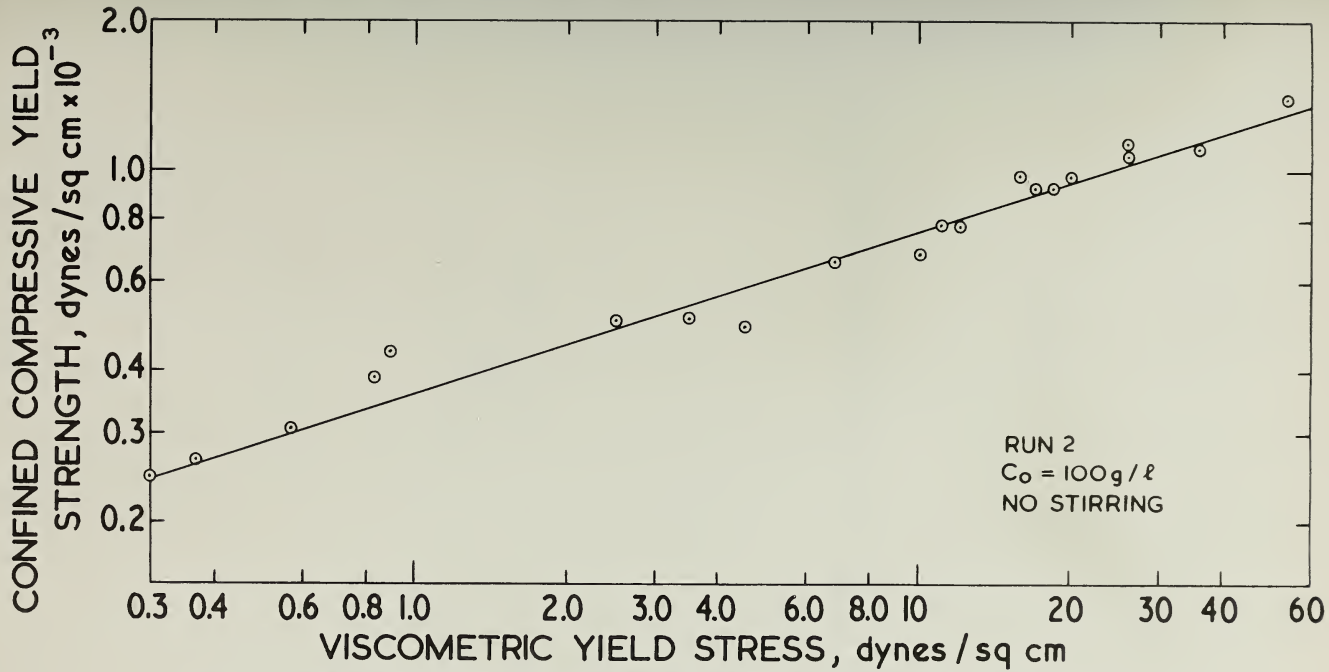

FIGURE 3. RELATIONSHIP BETWEEN RHEOLOGICAL PROPERTIES OF SLUDGE AS CALCULATED FROM VISCOMETER AND SEDIMENTATION DATA

APPENDIX VI

INFLUENCE OF BIOLOGICAL VARIABLES ON THE PHYSICAL PROPERTIES OF ACTIVATED SLUDGE

by

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and
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Prepublication Manuscript

INFLUENCE OF BIOLOGICAL VARIABLES ON RHEOLOGICAL PROPERTIES OF ACTIVATED SLUDGE

Richard I. Dick, Sajal K. Chakrabarti, and Gloria L. McCutcheon

INTRODUCTION

The effectiveness and cost of waste treatment by the activated sludge process depends, in large measure, on the physical properties of the activated sludge formed. Sludges with unfavorable physical properties settle poorly. This creates difficulty in obtaining concentrated sludge for return to the aeration tank which, in turn, may impair the quality of the effluent and increase the volume of sludge which must be wasted from the process. Similarly, the cost of treatment and ultimate disposal of waste activated sludge is increased if the sludge has adverse physical properties. Such sludges are difficult to concentrate for economical digestion, transport, or combustion, require higher doses of conditioning chemicals, and cause a reduction in the capacity of sludge dewatering equipment.

In spite of the importance of the physical properties of activated sludge, reliable techniques for measuring sludge properties are lacking. The sludge volume index has long been used as the only measure of the physical properties of activated sludge. While the SVI of an activated sludge is easy to determine and may be useful for routine treatment plant control, it is not an adequate description of the physical nature of a sludge. The basic nature of the sludge volume index was investigated by Dick and Vesilind (1969) who reported that the SVI was influenced in varying and unpredictable degrees by various physical properties of sludges and that it is seriously influenced by anomolies associated with the small cylinder used in the laboratory test.

Use of basic rheological measurements has previously been suggested (Dick and Ewing, 1967) as a more fruitful method for monitoring sludge quality and relating it to process performance. Wood (1970) found that rheological measurements were the best means for relating activated sludge properties to its flotation behavior, and Geinopolos and Katz (1964) reported that the capacity of a collector for a flotation unit was related to the rheology of the sludge being collected. Dick (1969b) related deviations in the settling behavior of activated sludge from conventional theory to the rheological properties of the suspension, and Colin (1970) used rheological measurements to assess the conditioning effect of polyelectrolytes.

Realizing that the behavior of activated sludge in treatment processes is influenced by its rheological nature, it is necessary to have information on the influence of variables in the activated sludge process on the rheology of the sludge produced. The purpose of this paper is to present some preliminary results of this type.

RHEOLOGY

Rheology is the study of the response of a material to an applied stress. Most pure liquids afford a simple illustration of one type of rheological behavior. They exhibit the well known Newtonian type of behavior in which the velocity gradient is directly proportional to the applied stress - the proportionality constant relating the two is called viscosity. Hookeian or elastic solids afford another simple illustration. In this case, distortion is proportional to applied stress and the constant relating the two is the modulus of elasticity. Between the extreme and ideal types of behavior described by Hooke and Newton many more complex types of behavior are possible. The reader is referred to sources such as Scott Blair (1969)

and Reiner (1969) for a complete discussion of types of rheological behavior.

If in a suspension such as activated sludge a continuous network of particles is formed, then one might expect that the material would behave as a solid until the internal structure was destroyed and that when greater stresses were applied the material would flow somewhat as a liquid. Indeed this type of rheological behavior, called plastic behavior, has been found with activated sludge (Dick and Ewing, 1967). As originally described by Bingham (1922), the behavior of a plastic material may be described as

$$\tau = \tau_y + \eta \frac{dv}{dx} \qquad (1)$$

where τ is shearing stress, τ_y is the yield stress, η is the coefficient of rigidity or plastic viscosity, and $\frac{dv}{dx}$ is the velocity gradient or rate of shear. Determination of the values of τ_y and η affords basic measures of the strength of the solid phase of the suspension and of the flow characteristics of the two phase system. It should be noted that it sometimes is difficult experimentally to distinguish between plastic materials and materials exhibiting a related rheological property called pseudoplasticity. It is thus appropriate to consider the value of τ_y in equation (1) to be an apparent value realizing that the material may not fit Binghams ideal model exactly.

It might also be anticipated that activated sludge would display another rheological property, thixotropy, and indeed such behavior is commonly found. Thixotropy is a time dependent rheological characteristic which occurs when breakdown of a suspension occurs as a function of time as well as of shear rate. Thus, if a suspension of activated sludge is continuously sheared at a constant rate, the resulting shearing stress will normally diminish with time approaching some equilibrium value at which the rate of breakdown of

the sludge particles is equal to their rate of reformation.

VISCOMETRY

As suggested by equation (1), the rheological properties of yield strength and plastic viscosity may be determined by measuring shearing stress and velocity gradient at several flow conditions. This can be done conveniently in a coaxial cylinder viscometer. In such a viscometer, a sludge sample is placed in the annular space between two coaxial cylinders and one cylinder is rotated relative to the other to produce velocity gradients and hence shearing forces. The velocity gradient is deduced by observing the relative angular velocity, and shearing stress is computed from measuring torque on one of the cylinders. The basis of such calculations has been discussed previously (Dick and Ewing, 1967) and is described in detail by Van Wazer et al. (1963).

Unique requirements of rotational viscometers used for observing the rheology of activated sludge were discussed by Dick and Ewing (1967) and the instrument used in this work was a refinement of the one described by them. Figure 1 shows the geometry of the cylinders. The outer cylinder was rotated by means of a continuously variable speed drive and the resulting torque on the inner cylinder was calculated by observing the deflection of the calibrated wire by which it was suspended.

Basic procedures for operating the viscometer were as described by Dick and Ewing (1967), except that activated sludge samples were introduced into the viscometer through the hollow drive shaft at the bottom of the outer cylinder.

EXPERIMENTAL PLAN AND PROCEDURES

In order to observe the influence of biological variables on the physical properties of activated sludge, the rheological behavior of activated

sludges cultivated under various controlled conditions was examined. Continuous flow activated sludge units such as shown in Figure 2 were used. Solids recirculation was accomplished by aspiration of settled sludge under the baffles separating the aeration and sedimentation compartments. Feed was stored in a 4°C refrigerator and, for each desired loading condition, was pumped at a constant rate to the continuous flow treatment system. The mixed liquor suspended solids concentration was maintained at the desired level by daily wasting of sludge. In the studies of the influence of organic loading intensity on physical behavior of sludges, no rheological observations were made until "steady-state" was reached as indicated by a constant degree of COD removal and the absence of any trend in the amount of sludge synthesis.

Studies on the effect of extended periods of endogenous conditions on sludge characteristics were conducted by discontinuing feed and removing the baffle from the activated sludge system. Studies of the changes in physical properties of sludges which occurred during the feeding cycle were conducted by discontinuing the feed, removing the baffle from the activated sludge unit, and operating it as a batch feed system operating on a 24-hr cycle.

Preliminary studies showed that activated sludge grown in laboratory units using chemically defined substrates bore little physical resemblance to real activated sludge. Hence the laboratory unit was seeded with activated sludge from the Urbana-Champaign, Illinois Sanitary District Main Treatment Plant and primary sedimentation tank effluent from the same plant was used as feed. Unfortunately, it was not possible to achieve high organic loadings using this waste because the unit became hydraulically overloaded. Hence it was necessary to change to a more concentrated synthetic substrate for those studies identified as "high-loading" experiments. To simulate waste of the

nature commonly encountered, an artificial waste consisting of dry dog food (Gaines Meal), toilet tissue (Scott Soft Weave), urea, and inorganic constituents was used. The synthetic waste was the same as used by Hunter et al. (1966) except that the toilet tissue concentration was 580 mg/l. The dog food and toilet tissue were ground and shredded and mixed with a small quantity of water in a blender for 5 min prior to addition to the synthetic waste. The suspended solids content of the artificial waste was approximately 3000 mg/l, the BOD was 2200 mg/l, and the COD was 2400 mg/l.

COD, BOD and SVI measurements were conducted according to Standard Methods (1965). Suspended solids were measured using the glass fiber filter method described by Gratteau and Dick (1968). Dehydrogenase enzyme activity was measured using the method proposed by Ford et al. (1966) although the reader is referred to a recent paper on the subject by Patterson et al. (1969) which appeared after this work was completed.

Equipment was available to permit 3 or 4 continuous flow activated sludge units to be operated simultaneously. To cover the desired range of loading factors it was necessary to make several different runs and a new sample of seed sludge was used at the commencement of each individual run. In the low loading studies (Chakrabarti, 1968), run A consisted of units operating at 0.08, 0.12, and 0.16 lb/BOD/day/lb MLSS and run B included units operating at 0.20, 0.38, 0.49, and 0.61 lb/BOD/day/lb MLSS. In the high loading study (Caban, 1969), three runs were used to span the desired range of loading factors; run C - 0.15, 0.30, and 0.45 lb/BOD/day/lb MLSS; run D - 0.60, 0.90, and 1.4 lb/BOD/day/lb/MLSS; and run E - 2.0, 3.0, and 4.0 lb/BOD/day/lb MLSS.

To permit comparison at the same concentration of the yield strength and plastic viscosity of sludges produced under different organic loading

conditions, it was necessary to make rheological investigations over a range of suspended solids concentrations. To achieve a range of concentrations, mixed liquor was thickened or diluted with effluent. Four different suspended solids concentrations within the range of about 1000 or 1500 mg/l to 3500 mg/l were normally examined at each organic loading intensity. Then, by plotting yield strength or plastic viscosity as a function of concentration for each loading, values could be selected at any desired concentration for purposes of comparison.

RESULTS AND DISCUSSION

Effect of Organic Loading Intensity

The yield strength over a range of suspended solids concentrations of sludges cultivated at various organic loading intensities in the low loading study are shown in Figure 3. Similar data from the high loading study are shown in Figure 4. It is seen that in both cases, the yield strength varied with concentration according to the relationship

$$\tau_y = je^{kc} \qquad (2)$$

where j and k are constants for a particular sludge. This is the same relationship reported from earlier studies with activated sludge (Dick and Ewing, 1967).

In Figures 3 and 4, it may be seen that each individual run tended to produce its own family of curves. This becomes more apparent when the yield strength of activated sludge at various concentrations is plotted as a function of loading intensity as in Figure 5. It is seen that similar trends were indicated in runs A and B but the relationship between loading and yield strength was not continuous between the two runs. This can be attributed to the fact that different samples of seed sludge were used to start the two

units. The difference in the physical characteristics of the organisms comprising the activated sludge persisted in spite of the fact that the original seed had been essentially lost due to sludge wastage before the rheological observations were made. The same phenomena was observed in the high loading studies although the scale of the plot of loading versus yield strength in Figure 6 disguises the discontinuities between individual runs.

This variation in physical properties of sludges attributable to differences in the nature of organisms present can also be seen in Figure 7. There, the plastic viscosity of sludges produced in the high loading study is shown as a function of concentration. The upper line represents a reasonable fit for all data obtained from runs C and E and shows that the plastic viscosity varied as a function of suspended solids concentration but was not highly dependent on the organic loading. However, data from the family of curves produced by run D form their own separate line indicated by the lower curve in Figure 7. For a given sludge, the plastic viscosity varied with suspended solids concentration and was not a function of loading. However, as indicated by the great difference between the two curves, plastic viscosity is highly dependent upon the nature of the organisms which comprise the sludge which develops under any particular loading condition.

The morphologic studies required to interpret the specific cause for the change in rheological characteristics from run to run were not made. However, recent studies by Wood (1970) confirm that changes in sludge rheology under given conditions are attributable to population shifts amongst the organisms comprising the sludge.

It is interesting to note that performance of the activated sludge units

in terms of BOD removal was quite uniform and did not reflect the differences in the physical properties of the organisms which predominated during the various runs. Also, the dehydrogenase enzyme activity varied continuously in a predictable manner as illustrated in Figure 8 and was not influenced by the physical differences in the organisms.

The standard measurement of sludge physical properties, the sludge volume index, was not sufficiently sensitive to detect the basic differences in the sludge organisms present during the preliminary runs. Sludge volume index measurements obtained during the high loading studies are shown in Figure 9. They have been recorded at equal suspended solids concentrations so that differences normally attributable to measurement variations in suspended solids concentrations have been eliminated.

Changes in Physical Properties during Aerobic Digestion

During aerobic digestion, yield strength of activated sludge changed both because of the change in the physical nature of the solids and because of the decrease in suspended solids concentration. To separate these two effects yield strengths during aerobic digestion were expressed as a percentage of the yield strength of a control sludge where the control sludge was defined as a sample of equal concentration and loading intensity which had not been exposed to endogenous conditions. Results from two different sludges are shown in Figure 10. It is seen that pronounced changes in the physical nature of the sludge solids occurred during aerobic digestion and after six days the sludge solids had only 10-15 percent of their initial yield strength. As might have been anticipated, the sludge produced at the higher organic loading intensity was able to sustain itself under endogenous conditions without pronounced change in physical properties for a day while the sludge grown under leaner conditions changed from the onset of endogenous

conditions.

Plastic viscosity also decreased during aerobic digestion. However, the change was much less pronounced than the change in yield strength.

Changes in Physical Properties Following Feeding

To determine the physical response of activated sludge to feeding, the rheological properties of a sludge acclimated to a 24-hr feeding cycle was monitored. Typical results are shown in Figure 11. It is seen that dramatic changes occurred, particularly in yield strength. The wide scatter in yield strength data during the first hour was caused by the fact that the sludge sample was changing appreciably during the period of inspection in the viscometer. Also, in an attempt to accurately define the early portion of the yield strength curve, samples were collected during several successive feeding cycles and all of those data are included on the same curve. The concentration of suspended solids in the batch yield changed somewhat with time because of synthesis and endogenous respiration; however, during the run for which data are shown in Figure 10, suspended solids did not fall below 1300 nor above 1700 mg/l and this change in solids content is inadequate to explain the orders of magnitude change in yield strength. Rather, this change was caused by a pronounced change in the physical nature of the activated sludge solids in response to feeding.

SUMMARY AND CONCLUSIONS

Although the design, performance, and cost of activated sludge waste treatment plants is highly dependent upon the physical properties of the activated sludge produced, little is known about the effect of process variables on physical behavior of the sludge. The only parameter commonly used to express the physical nature of activated sludge, the sludge volume index, is influenced by many separate sludge properties and by laboratory test

conditions and hence does not provide sufficient and interpretable information on the physical properties of sludge. In this study, more fundamental measures of the properties of suspensions, yield strength and plastic viscosity have been used. These parameters have more direct influence on the performance of sludge treatment processes such as thickening and flotation than does the more conventional SVI value. Results of preliminary studies on the influence of biological variables on yield strength and plastic viscosity are presented here.

A yield strength of a particular activated sludge depends on its concentration and the organic loading intensity. Yield strength increases exponentially with suspended solids concentration and also increases significantly and continuously as the organic loading intensity is increased. However, yield strength is also influenced by the nature of the particular organisms which comprise the sludge, and two sludges of equal concentration and organic loading grown on the same waste and giving the same biological performance may display different physical properties if they are comprised of different flora.

The plastic viscosity of a sludge of given biological composition is dependent only on the suspended solids concentration and is not markedly influenced by a change in organic loading. However, again shifts in biological population may produce significant changes in plastic viscosity without accompanying changes in solids concentration, organic loading, or biological process performance.

Yield strength decreases significantly during aerobic digestion. Reductions of 85-90 percent were observed within six days.

Remarkable changes in the yield strength of activated sludge occur following contact with substrate. In the 24 hr batch feeding studies reported here,

the yield strength of sludge increased by as much as two orders of magnitude within the first 15 to 20 min following feeding, and then declinsed.

These changes in sludge rheology are caused by changes in the basic physical nature of the sludge. While they must influence the performance of the biological process and of waste sludge treatment processes, for the most part, they remain undetected by standard measures of the physical characteristics of sludge.

ACKNOWLEDGEMENTS

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REFERENCES

Bingham, E. C., "Fluidity and Plasticity," McGraw-Hill Book Co., New York (1922).

Caban, G. L., "Physical Characteristics of Activated Sludge under High Loading Conditions," Undergraduate Special Problem, Department of Civil Engineering, University of Illinois, Urbana (1969).

Chakrabarti, S. K., "Changes in Some Physical Properties of Activated Sludge under Different Biological Conditions," Thesis submitted in partial fulfillment for the degree of Master of Science, University of Illinois, Urbana, 65 pp. (1968).

Colin, F., "Application de Techniques Rheologiques a l'etude des Boues Residuaires," la Tribune du CEBEDEAU, 23, 6317, 178-187 (April 1970).

Dick, R. I., "Thickening Characteristics of Activated Sludge," In Advances in Water Pollution Research, Proceedings of Fourth International Conference on Water Pollution Research, Prague, 1969, 625-642 (1970).

Dick, R. I., and Ewing, B. B., "The Rheology of Activated Sludge," Journal Water Pollution Control Federation, 39, 4, 543-560 (1967).

Dick, R. I., and Vesilind, P. A., "The Sludge Volume Index - What Is It?" Journal Water Pollution Control Federation, 41, 7, 1285-1291 (1969).

Ford, D. L., Eckenfelder, W. W., and Yang, T., "Dehydrogenase Enzyme as a Parameter of Activated Sludge Activities,"Proceedings 21st Industrial Waste Conference, Purdue Univ., Eng. Ext. Ser. 121, 534-543 (1966).

Geinopolis, A., and Katz, W. J., "A Study of a Rotating Cylinder Sludge Collector in the Dissolved Air Flotation Process," Journal Water Pollution Control Federation, 36, 6, 712 (June 1964).

Gratteau, J. C., and Dick, R. I., "Activated Sludge Suspended Solids Determinations," Water and Sewage Works, 115, 10, 468-472 (1968).

Hunter, J. V., Genetelli, E. J., and Gilwood, M. E., "Temperature and Retention Time Relationships in the Activated Sludge Process," Proceedings 21st Industrial Waste Conference, Purdue Univ., Eng. Ext. Ser. 121, 953-963 (1966).

Patterson, J. W., Brezonik, P. L. and Putnam, H. D., "Sludge Activity Parameters and Their Application to Toxicity Measurements and Activated Sludge," Proceedings 24th Industrial Waste Conference, Purdue Univ., Eng. Ext. Ser. 135, 127-154 (1969).

Reiner, M., "Deformation, Strain, and Flow," H. K. Lewis and Co., Ltd., London, 347 pp. (1969).

Scott Blair, G. W., "Elementary Rheology," Academic Press, New York, 158 pp. (1969).

Standard Methods for the Examination of Water and Waste Water, 12th Ed., Amer. Pub. Health Assoc., New York, 769 pp. (1965).

Van Wazer, J. R., Lyons, J. W., Kim, K. Y., and Colwell, R. E., "Viscosity and Flow Measurement, " Interscience, New York (1963).

Wood, R. F., "The Effect of Sludge Characteristics upon the Flotation of Bulked Activated Sludge," Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, University of Illinois, Urbana, 143 pp. (1970).

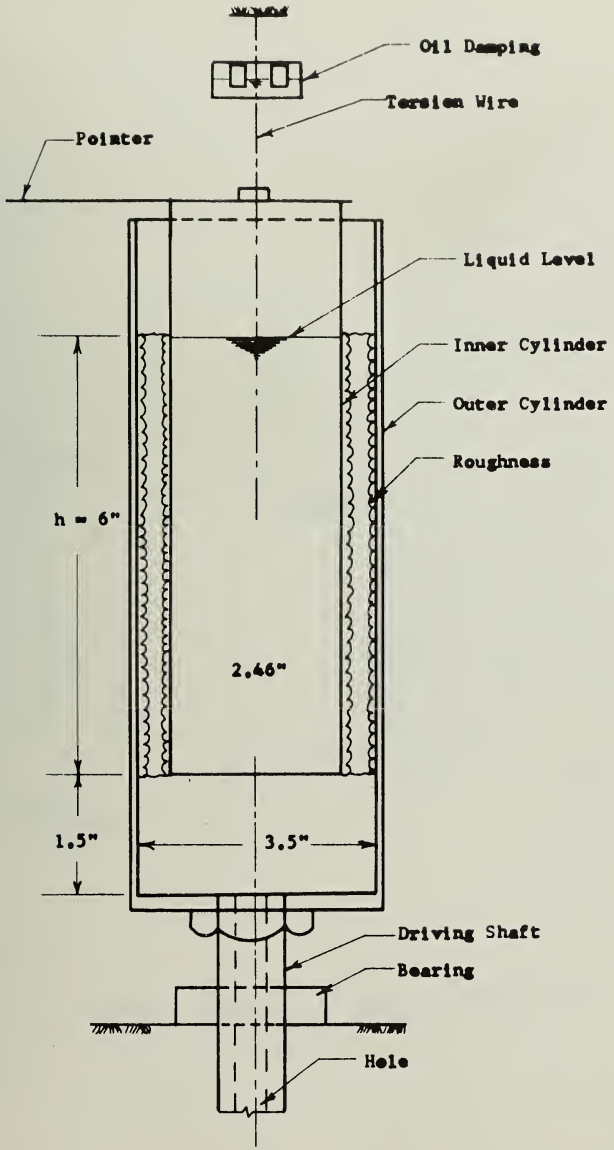

FIGURE 1. COAXIAL CYLINDER VISCOMETER

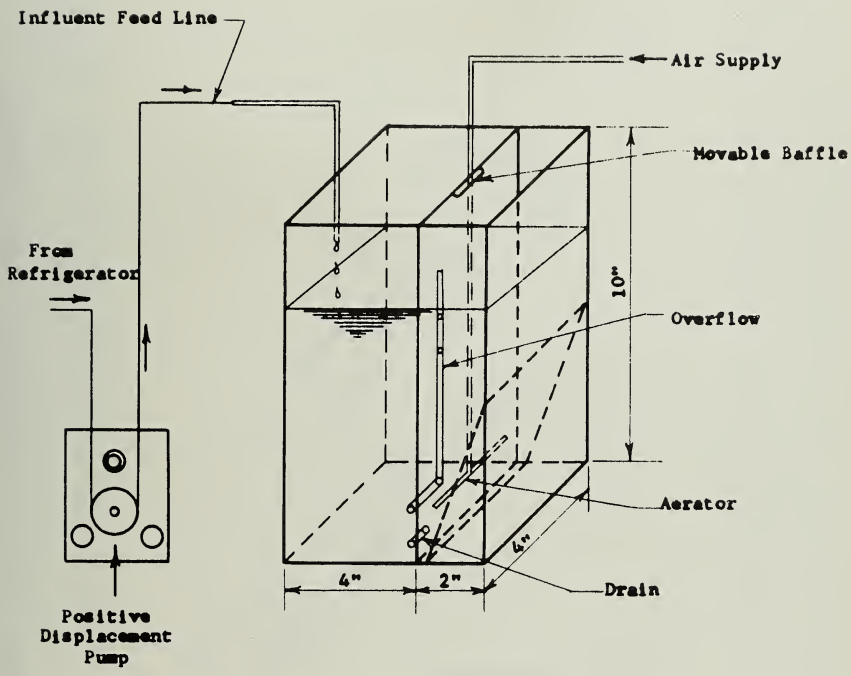

FIGURE 2. SCHEMATIC DIAGRAM OF CONTINUOUS FLOW ACTIVATED SLUDGE UNIT

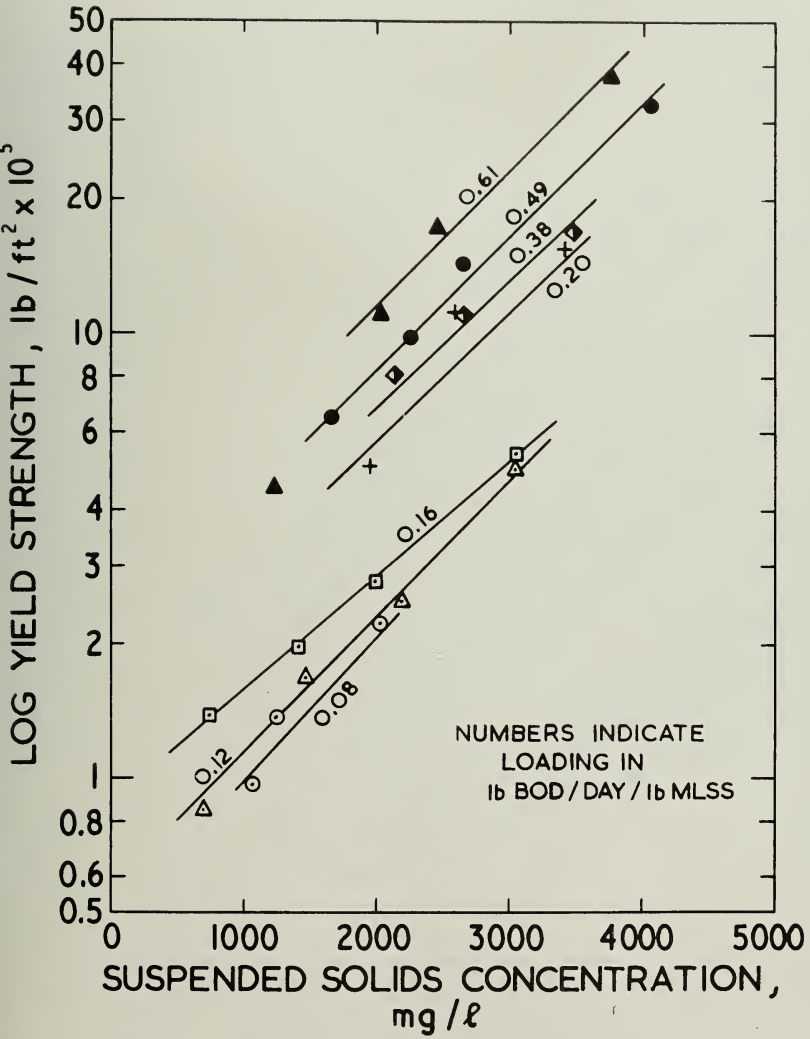

FIGURE 3. VARIATION OF YIELD STRENGTH WITH SUSPENDED SOLIDS CONCENTRATION - LOW LOADING STUDIES

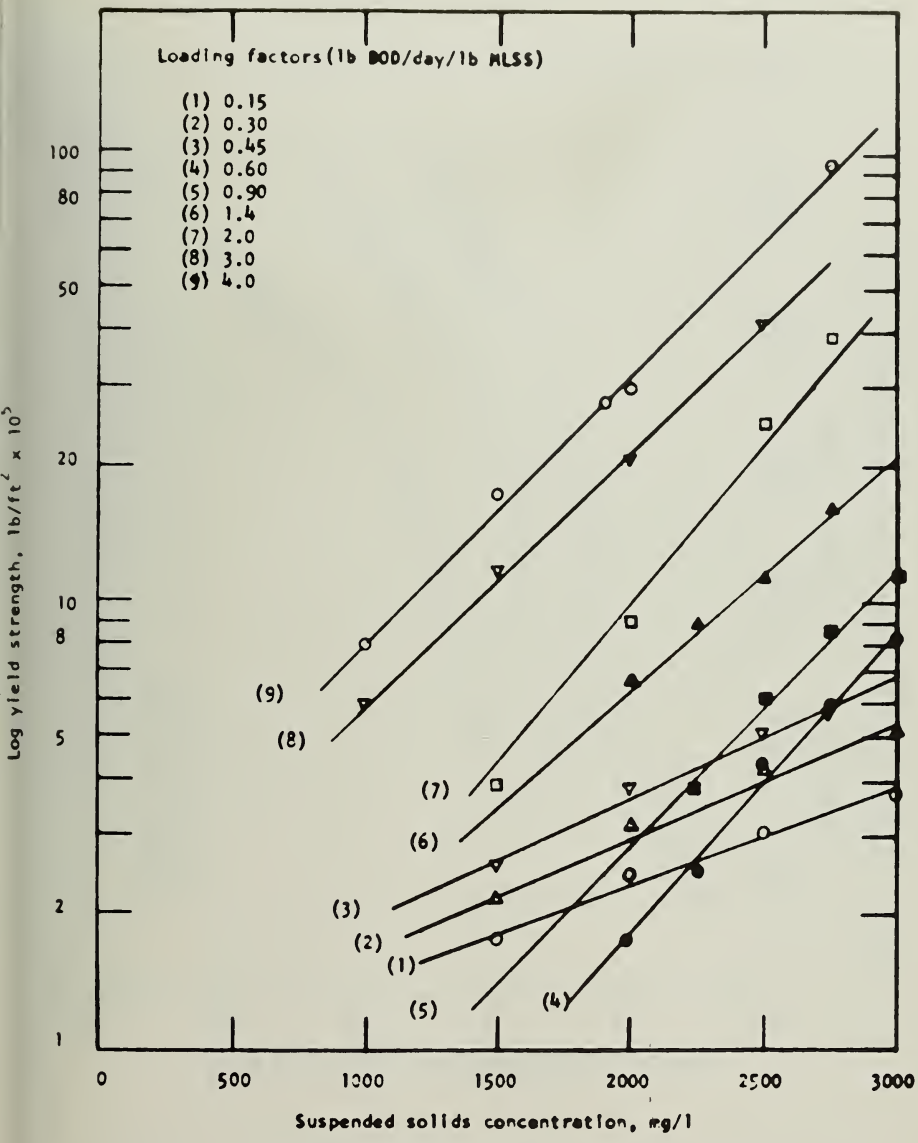

FIGURE 4. VARIATION OF YIELD STRENGTH WITH SUSPENDED SOLIDS CONCENTRATION - HIGH LOADING STUDIES

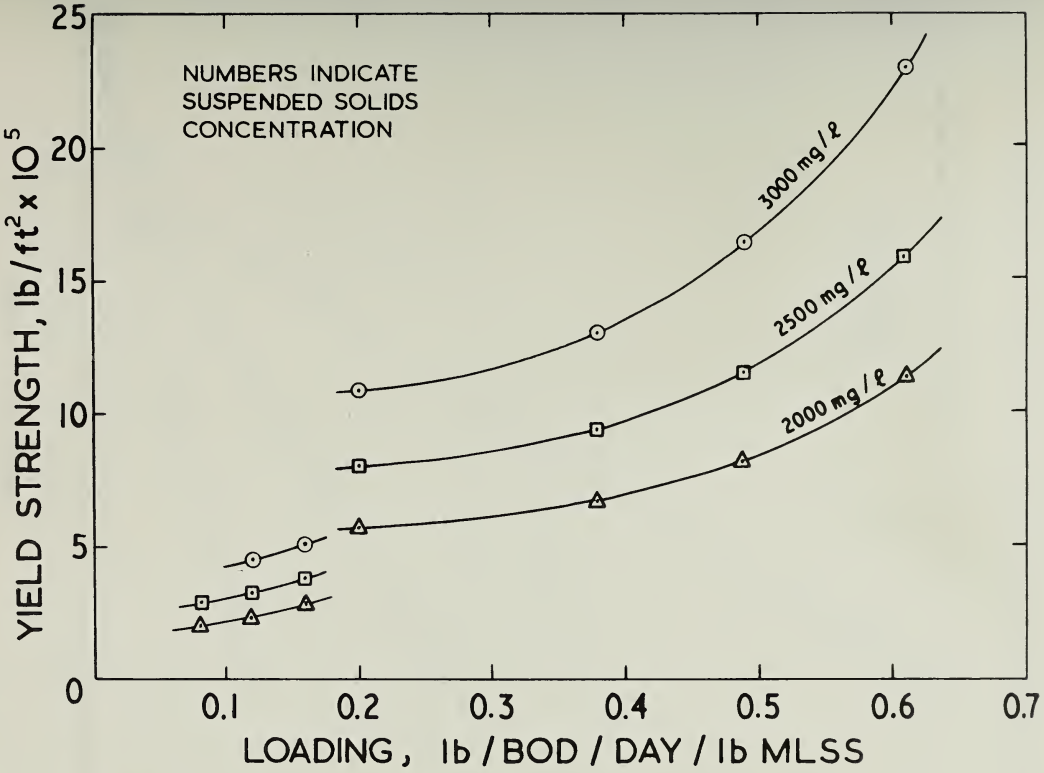

FIGURE 5. INCREASE IN YIELD STRENGTH WITH INCREASED ORGANIC LOADING - LOW LOADING STUDIES

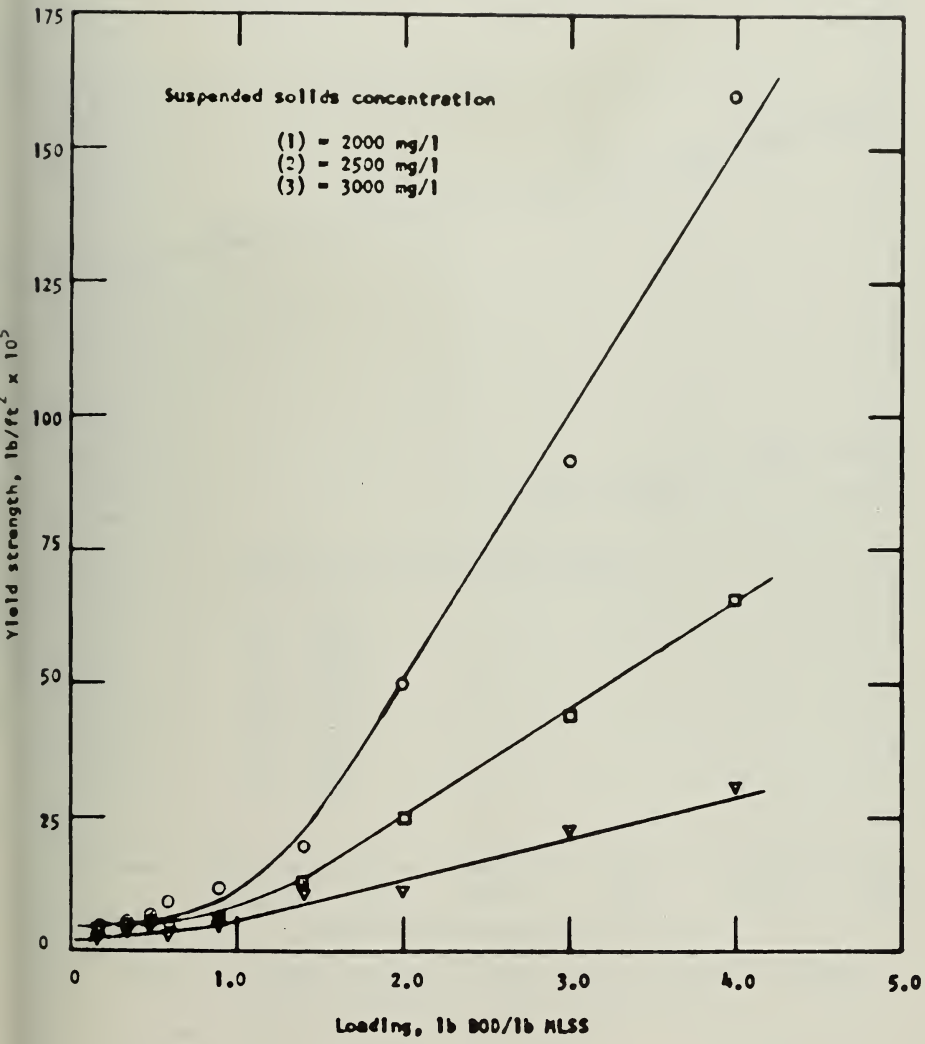

FIGURE 6. INCREASE IN YIELD STRENGTH WITH INCREASED ORGANIC LOADING - HIGH LOADING STUDIES

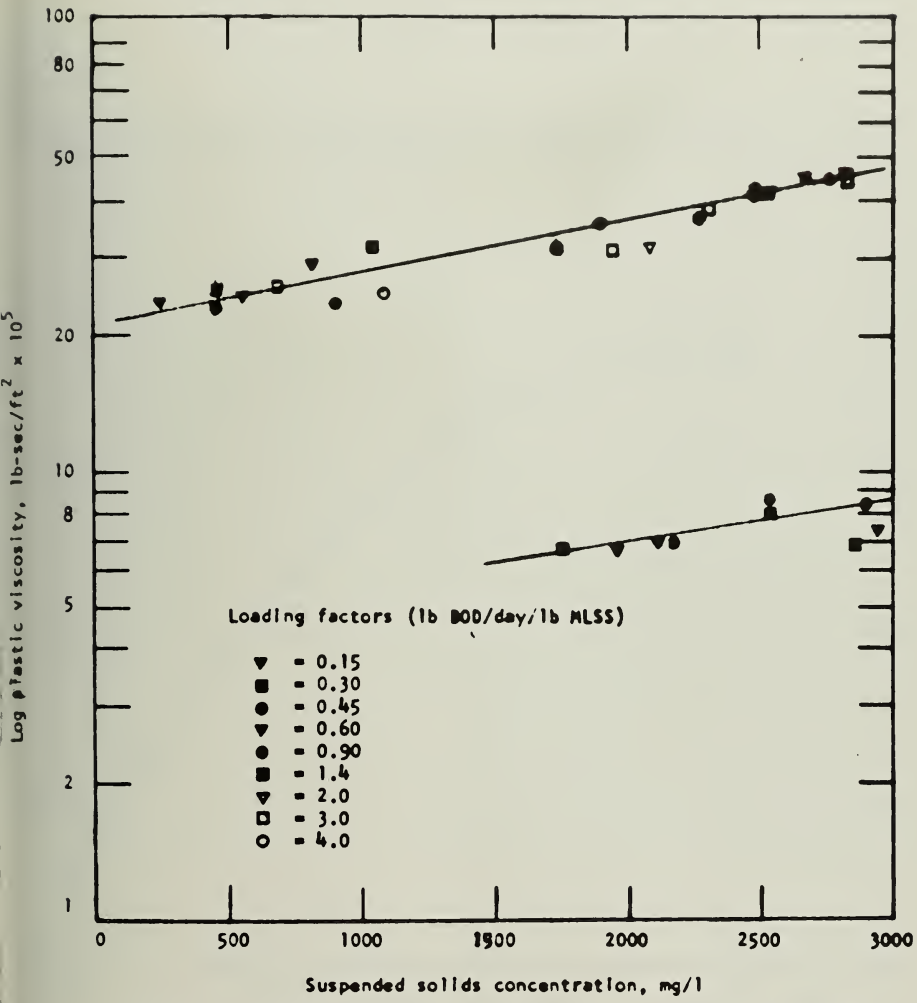

FIGURE 7. CHANGES IN PLASTIC VISCOSITY DUE TO CHANGES IN SUSPENDED SOLIDS CONCENTRATION - HIGH LOADING STUDIES

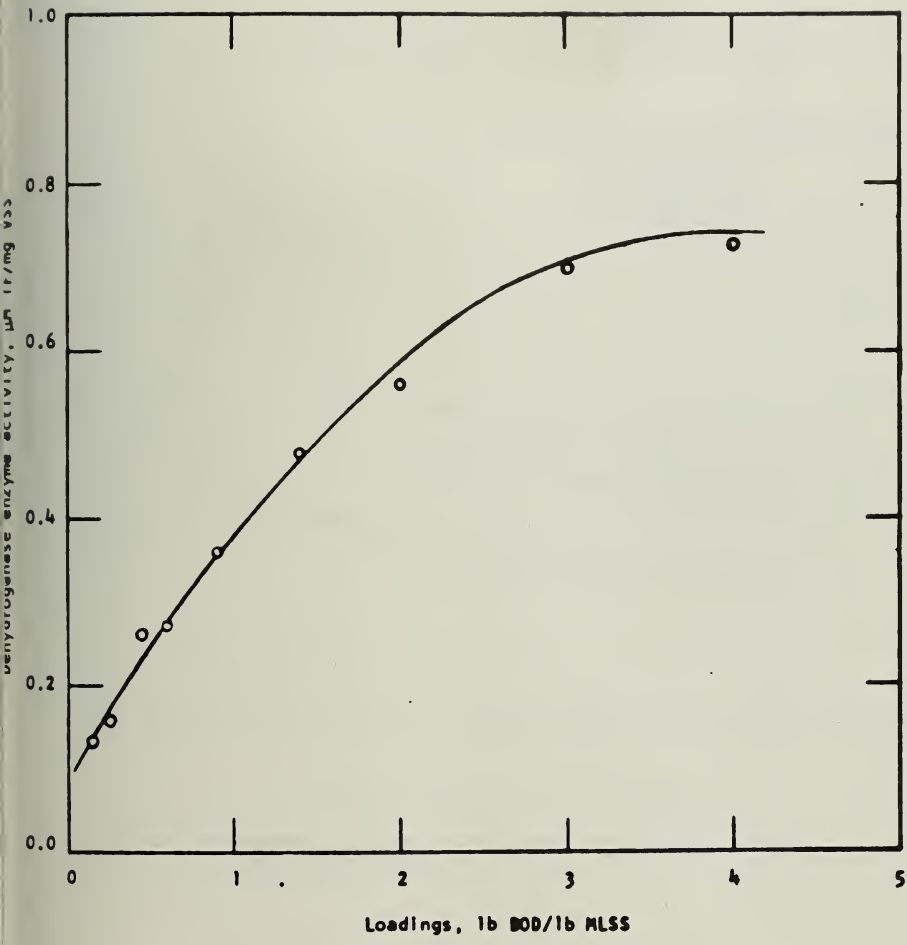

FIGURE 8. DEHYDROGENASE ENZYME ACTIVITY AT DIFFERENT ORGANIC LOADINGS - HIGH LOADING STUDIES

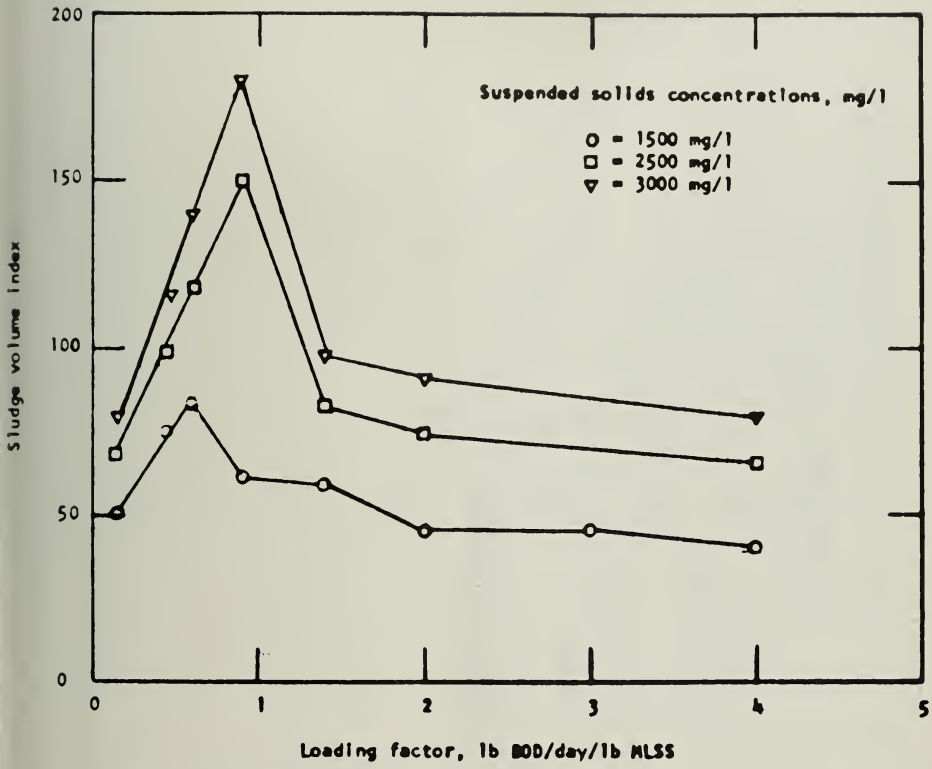

FIGURE 9. CHANGE IN SLUDGE VOLUME INDEX WITH ORGANIC LOADING - HIGH LOADING STUDIES

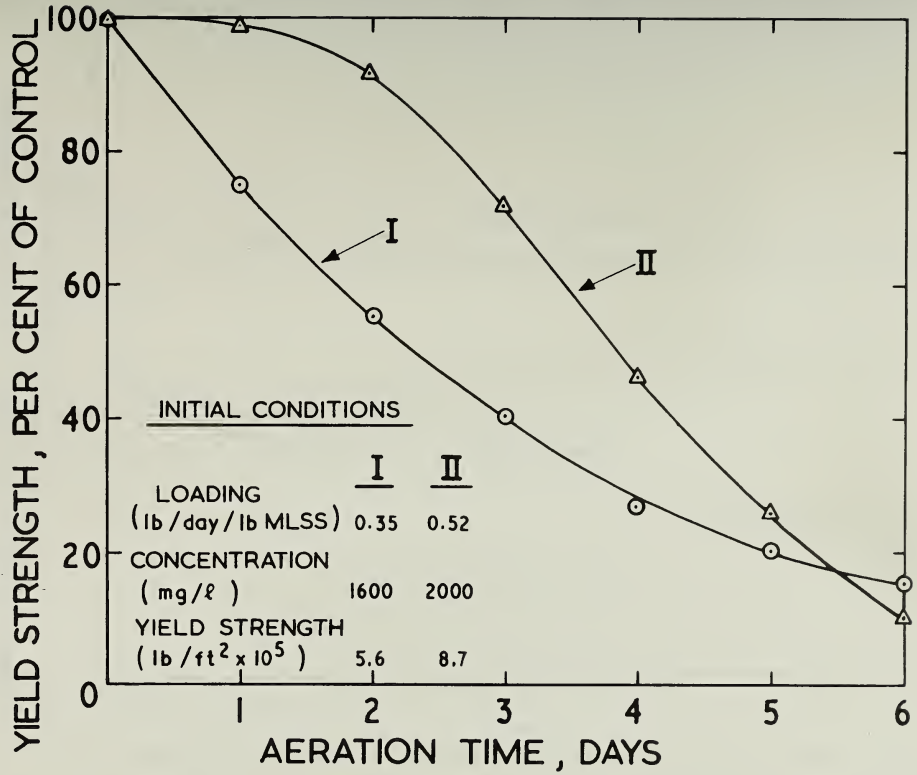

FIGURE 10. DECREASE IN YIELD STRENGTH DURING AEROBIC DIGESTION

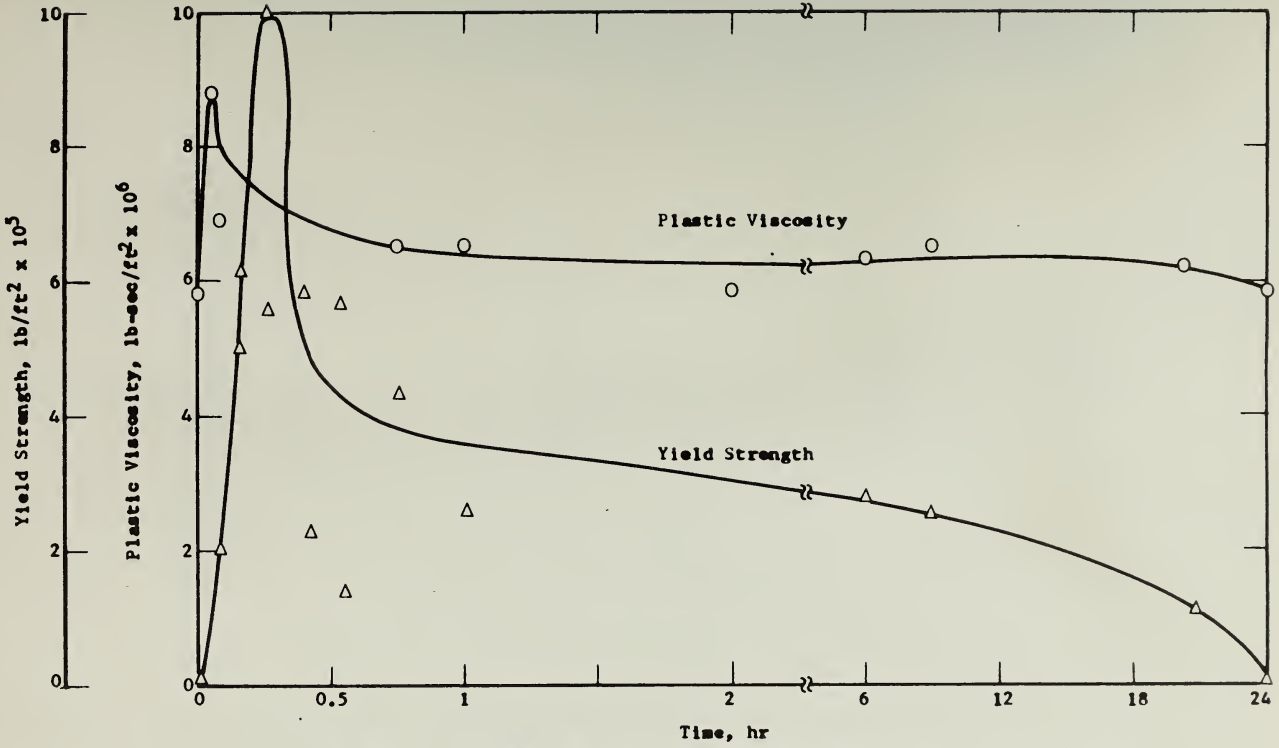

FIGURE 11. CHANGES IN PHYSICAL PROPERTIES DUEING INITIAL CONTACT PERIOD

APPENDIX VII

THICKENING

by

Richard I. Dick

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Advances in Water Quality Improvement -
Physical and Chemical Processes
Edited by E. F. Gloyna and W. W. Eckenfelder, Jr.
University of Texas Press, Pages 358-369
1970

THICKENING

Richard I. Dick
University of Illinois, Urbana

Physical, biological, and chemical methods of waste treatment share the common goal of concentrating pollutional material into a small portion of the total waste flow. This permits return of the bulk of the flow to the environment, but leaves behind a troublesome residue. Most often, the materials removed from waste flows remain in the form of suspended solids. Typically, the solids are light and flocculent and cannot be consolidated readily into high concentrations for economical treatment and disposal.

The most economical means of reducing sludge volume is by thickening. To illustrate, thickening of a waste sludge from 3 percent to 9 percent solids by weight results in a three fold reduction in sludge volume. To accomplish an additional three fold volume reduction (to 27 percent solids) would require a dewatering process such as vacuum filtration. Burd (1) has indicated that the normal annual cost of gravity thickening is $1.50 to $5 per ton of dry solids, while the cost of vacuum filtration averages about $15 per ton of dry solids and ranges as high as $50 per ton.

Concentration of sludges by gravity thickening and flotation is considered here. It should be noted that the concepts discussed apply to the concentration of sludge as it occurs in any settling tank or flotation unit and are not restricted to basins called "thickeners" (5).

GRAVITY THICKENING

Analysis of the performance of full-scale continuous thickeners requires: (*a*) knowledge of the basic settling characteristics of the suspension being thickened, and (*b*) an understanding of the manner in which these basic settling properties govern the performance of a continuous thickener. Theoretical means are available to relate settling properties to continuous thickening. However, less is known about how to obtain data which reveal settling behavior to be expected in full-scale settling tanks. These two items are considered in the sections which follow.

Relationship between Settling Properties and Continuous Thickening

To predict the performance of a full-scale continuous thickener, it is necessary to know the settling velocity of the sludge being thickened at all concentrations which could occur in the thickener. Discussion of the problem of obtaining these data is reserved for the section which follows. Here, it is assumed that data indicative of actual settling behavior in a full-scale thickener are available, and their relationship to the performance of the thickener is explored.

It is necessary to know the settling velocity of the sludge at each concentration which could exist in a thickener because, for a given operating condition, the settling velocity of sludge at some limiting concentration determines the capacity of the suspension to pass solids to the bottom of the tank. To illustrate, consider first a batch thickener with no underflow. The downward flux of solids, G_B, at any point in the thickener is

$$G_B = c_i v_i$$

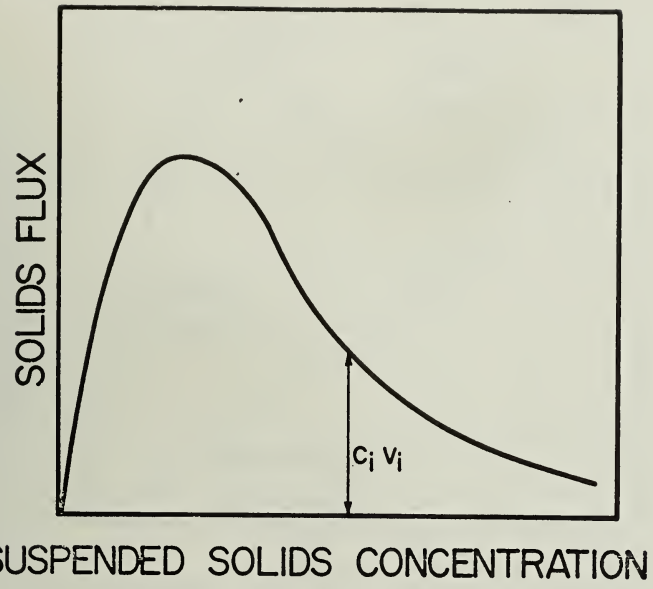

Figure 195. Typical batch flux curve.

where c_i is the concentration of sludge at that point, and v_i is the settling velocity corresponding to that concentration. A typical batch flux curve is shown in Figure 195. Note that the flux is zero when $c_i = 0$ and at extremely high concentrations where v_i approaches zero, and that G_B reaches a maximum at some intermediate concentration.

In a continuous thickener, withdrawal of solids from the bottom of the tank increases the rate of downward transport of solids. If solids and downward flow are considered to be uniformly distributed radially, the added flux, G_u, due to underflow, is:

$$G_u = c_i u \tag{2}$$

where u is the downward velocity of the suspension relative to the thickener walls due to sludge removal. In a thickener with cross-sectional area A, removal of sludge at volumetric underflow rate Q_u gives:

$$u = \frac{Q_u}{A} \tag{3}$$

Because the total rate of solids throughput in a continuous thickener is $Q_u c_u$, where c_u is the concentration of the underflow, the solids flux in a continuous thickener may be written as :

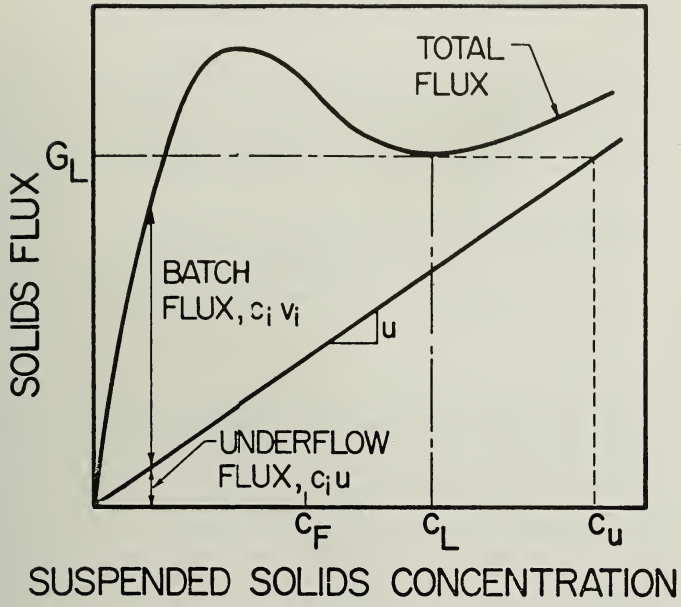

Figure 196. Total flux in a continuous thickener.

$$G_c = \frac{Q_u c_u}{A} = c_u u \tag{4}$$

Q_u and u thus are related inversely to the underflow concentration, c_u.

When a continuous thickener of area, A, is operated at some underflow velocity, u (corresponding to a desired underflow concentration, c_u), the total possible flux, G_c, for any concentration of the suspension, c_i, is the sum of Equations (1) and (2):

$$G_c = c_i v_i + c_i u \tag{5}$$

Figure 196 shows a plot of the total possible flux for solids concentrations which could occur in a continuous thickener, and illustrates relative contribution of gravity subsidence and underflow to solids flux. Note that the possible solids flux passes through some minimum value, G_L, between the feed concentration, c_F, and the underflow concentration, c_u. The suspension at concentration c_L thus limits the rate at which solids can reach the tank bottom and becomes a bottleneck in operation of the continuous thickener, for if solids are withdrawn at the desired underflow concentration, flux through the settling tank cannot exceed G_L. The required area for a thickener is, hence

$$A = \frac{Q_F c_F}{G_L} \tag{6}$$

where Q_F and c_F are the influent flow rate and solids concentration. If an area smaller than $Q_F c_F / G_L$ were to be provided, solids in the amount $Q_F c_F - AG_L$ would be lost over the effluent weir, for they could not be transmitted to the bottom of the thickener at a rate greater than G_L. To stop the loss of solids over the weir a compromise could be made in the desired underflow concentration so as to increase the bulk downward velocity, u, to the extent that the limiting solids flux would be increased to equal the actual solids loading rate.

While a total flux plot such as shown in Figure 196 is an instructive means of evaluating the behavior of a suspension in a thickener, the method is not convenient. This is because a separate plot (with a different slope on the underflow flux line) is needed to consider each alternate thickener area or underflow concentration.

An alternate, and more convenient, means of thickener analysis involves use of a batch flux curve. From Equation (4):

$$u = \frac{G_c}{c_u} \tag{7}$$

Hence the scope of a line connecting any point on the ordinate (G) axis of a flux plot with any point on the abscissa (c) gives the underflow velocity in a thickener with the corresponding flux and underflow concentration. From Equation (5), and Figure 197, it may be seen that if this operating line intersects the batch flux curve ($c_i v_i$) the intercept of the line on the ordinate axis will be ($c_i v_i + c_i u$) or the solids handling capacity of the suspension at concentration c_i when it is being thickened to c_u, the intercept on the abscissa. When the operating line is tangent to the flux plot, as in Figure 197, the intercept, G_c, is the maximum possible loading on the thickener, and the point of tangency is at c_L, the concentration of the suspension with the minimum capacity for transmitting solids under the operating conditions described by the operating line. Intersections of the operating line with the rising portion of the batch flux curve are not of concern if the concentration, c_i, corresponding to the point of intersection, is less than the feed concentration (or the concentration to which the feed is diluted at the inlet.[1]

By use of a flux plot such as shown in Figure 197, a variety of alternate thickener designs can be evaluated readily by selecting various possible underflow concentrations, drawing tangents from the c_u values to the flux curve, and observing the corresponding maximum flux curve, and observing the corresponding maximum flux values from the intersections with the ordinate axis. The thickener area required to produce various alternate thickened sludge concentrations may then be determined from Equation (5).

The flux plot may be used to describe performance of existing thickeners as well. The influence of a change in the volumetric feed rate or a change in the solids concentration of the feed may be quickly evaluated by plotting the resulting solids loading on the or-

[1]A more common method of showing the utility of a batch flux curve (16) is based on the work of Kynch (10). Kynch showed that in batch sedimentation, a slight concentration discontinuity is propagated upward at a velocity equal to $-dG/dc$. Such a discontinuity would form at the top of a layer of concentration c_L because of its inability to transmit solids at a rate faster than the limiting solids flux. In a continuous thickener, the rate limiting layer must be prevented from being propagated upward to avoid loss of solids over the effluent weir. This can be done by withdrawing solids at a rate sufficient to give a bulk downward velocity, u, equal to the rate of upward propagation of the layer in a batch test, $-dG/dc$. This rate is given by the slope of the tangent to flux curve as illustrated in Figure 199. The alternate derivation presented here is equivalent in utility to that developed by Kynch.

dinate axis, drawing a tangent to the flux curve, and observing the resulting underflow concentration.

Illustrative Problems

1. Determine the required area for a thickener which is to concentrate 0.3 mgd of waste-activated sludge from an initial concentration of 7,000 mg/l to 2 percent solids by weight. Settling characteristics of the activated sludge, which has excellent physical properties, are shown in Figure 198.

Solution: Figure 199 shows a solids flux plot obtained by multiplying each settling velocity in Figure 198 by its corresponding concentration. Operating line 1 is drawn as a tangent to the flux plot from the desired underflow concentration, 20,000 mg/l, and indicates that the maximum solids flux through the thickener is 13 lb/ft²/day. The required area is, hence

$$A = \frac{Q_F c_F}{G_L} = \frac{(0.3)\,(7{,}000)\,(8.34)}{13} = 1{,}350 \text{ ft}^2$$

2. Following construction of the thickener as prescribed by the calculations above, the

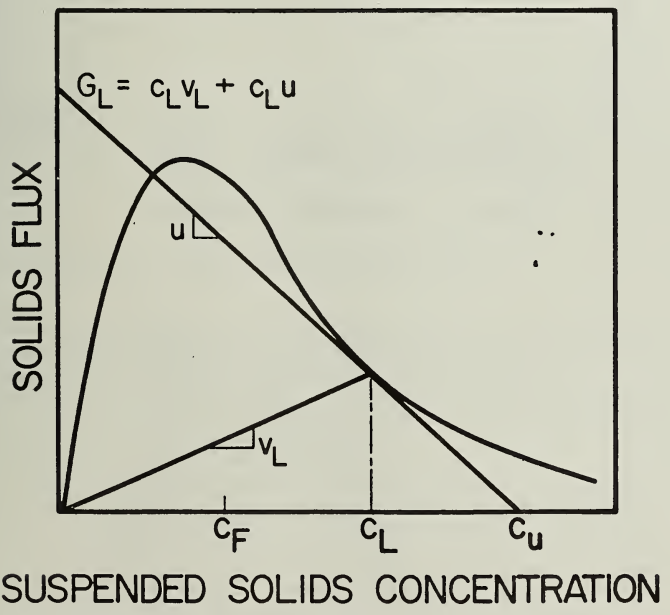

Figure 197. Use of flux curve to identify limiting conditions.

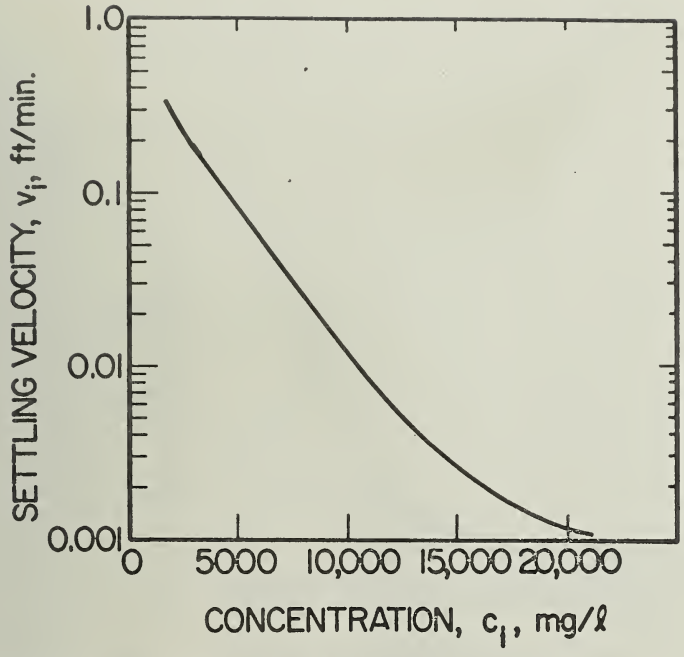

Figure 198. Settling properties of sludge considered in illustrative problem.

flow of waste-activated sludge increases to 0.4 mgd, and the feed sludge concentration increases to 8,000 mg/l. Physical characteristics of sludge solids are unaltered. What will be the consequence of continuing to withdraw sludge at 2 percent solids?

Solution: Solids are now being applied at 19.8 lb/ft²/day. But under the operating conditions, only 13 lb/ft²/day can reach the bottom of the tank. Thus 6.8 lb/ft²/day or 9,200 lb/day of solids will be lost over the effluent weir.

3. How can operation of the thickener be modified to avoid loss of solids?

Solution: The rate of removal of sludge from the thickener must be increased to increase the solids flux. Line 2 in Figure 199 shows the modified operating conditions. It is drawn as a tangent to the flux plot from the required solids flux, 19.8 lb/ft²/day, and shows that the underflow solids concentration must be decreased to about 17,500 mg/l to accommodate the increased loading on the thickener. Note that the sludge which limits the capacity of the thickener now has a concentration of about 12,500 mg/l.

Alternatively, and more laboriously, the modified conditions can be determined by use of a plot of Equation (5) as shown in Figure 200. The original operating conditions are shown as solid lines and illustrate the relative contribution of underflow and subsidence

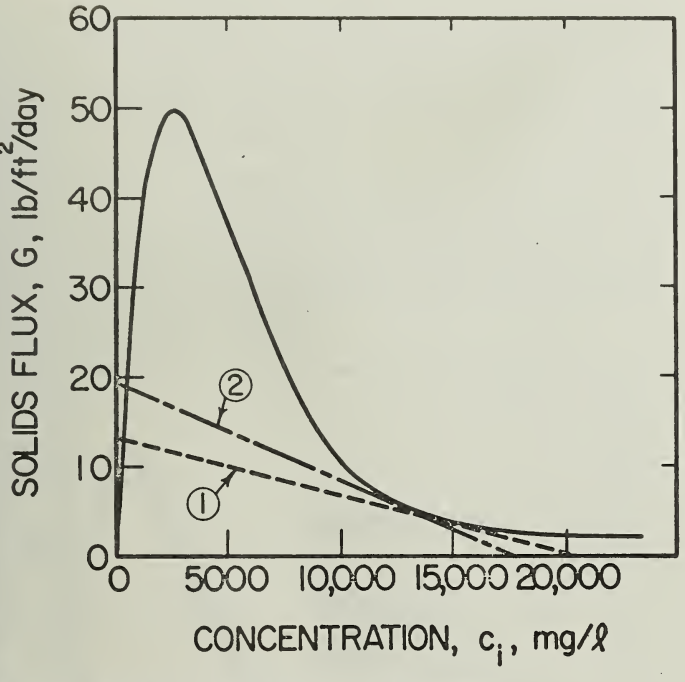

Figure 199. Operating conditions considered in illustrative problem.

to the solids handling capacity of the suspension. Note that the minimum solids flux at 14,500 mg/l agrees with the value obtained before. To increase the capacity of the thickener to receive solids, the underflow velocity (the slope of the underflow flux curve) must be increased as illustrated by the dashed lines in Figure 200. By trial-and-error, it is found, as before, that when the underflow rate is increased to 183,000 gpd (corresponding to an underflow concentration of 17,500 mg/l) the possible flux through the thickener is equal to the applied load, 19.8 lb/ft²/day.

Measurement of Settling Properties

The preceding analysis of continuous thickening was founded on the assumption that the settling velocity of any concentration of sludge *as it might exist in the full-scale continuous thickener* was known. It remains to show how these data may be obtained.

The settling velocity of various concentrations of sludge *as displayed in laboratory batch settling columns* can be determined readily. A transparent cylinder is filled with a uniformly dispersed sample of sludge of known concentration and a plot of the solids-

liquid interface position as a function of time is obtained. As illustrated in Figure 201, the initial slope of this curve, following a period of reflocculation, is the settling velocity of the sludge at its initial concentration under the laboratory batch-settling conditions.

Few opportunities are available to compare laboratory batch-settling results directly with the real settling properties of sludge in a full-scale thickener. However, sufficient evidence is available from laboratory data obtained under various conditions to realize that these data can be seriously misleading unless care is exercised in obtaining and interpreting them.

One obvious factor which can cause laboratory settling behavior to differ from sedimentation in a full-scale thickener is that the container boundary is more prominent in laboratory vessels. In order to make effective use of laboratory data, one must use a laboratory column large enough to reduce the wall effect significantly and understand the effect of the diameter chosen on the results obtained. Unfortunately, because of the complexity of the effect of the wall on sedimentation and because the effect is highly dependent on the type of suspension being observed, one can find convincing evidence in the literature to justify any column size selected.

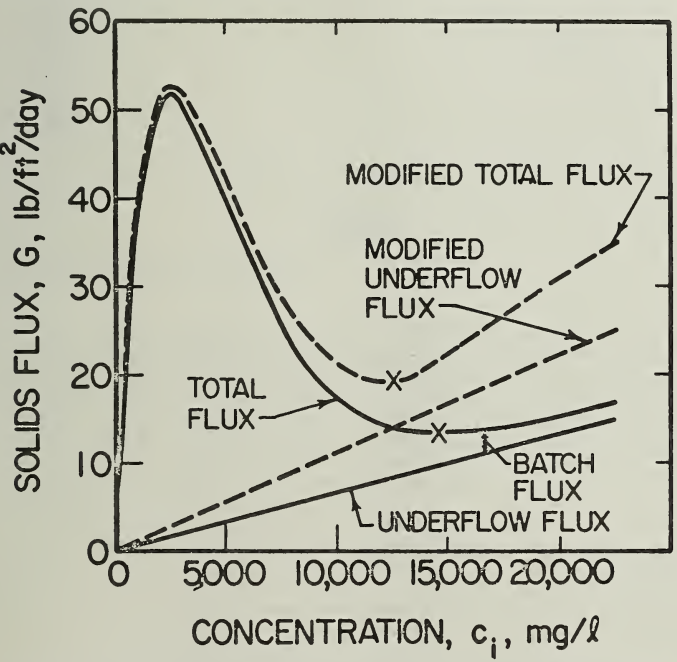

Figure 200. Relative significance of underflow and subsidence for the operating conditions considered in illustrative problem.

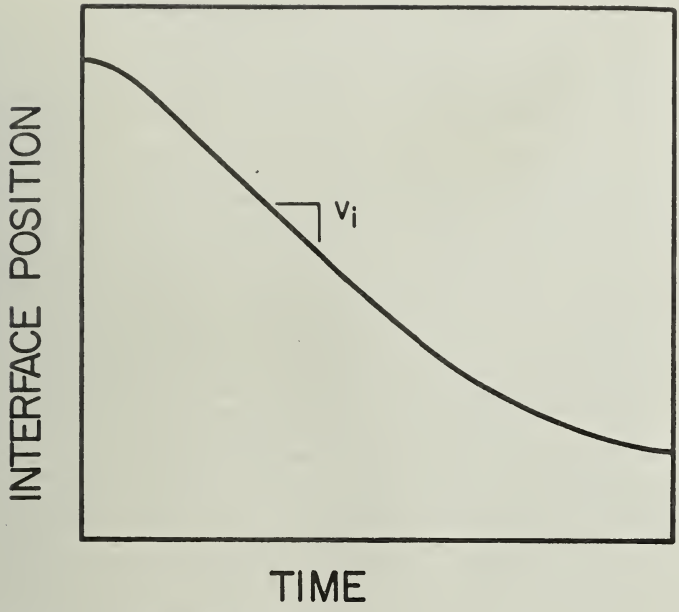

Figure 201. Typical batch settling curve.

Data for activated sludge presented by Vesilind (17) illustrate the complex effect of the cylinder wall. The smooth path along the wall provides a less tortuous means of escape for displaced liquid and thus tends to increase the rate of subsidence. This is counteracted by a tendency for arching of the sludge solids across the column, which reduces the observed subsidence rate. At relatively low concentrations, the hastening of subsidence because of flow of displaced liquid along the wall is the predominant effect, and sludge tends to settle faster in the laboratory than in the field. However, at higher concentrations the arching mechanism predominates, and sludges tend to settle more slowly in the laboratory than in the field.

The depth to which sludge is placed in laboratory settling columns can also influence results. The Kynch theory (10), on which much thickening work is based, supposes that settling velocity is independent of depth. While the theory is a valuable description of ideal settling behavior, it does not describe completely the actual settling behavior of the real suspensions encountered in waste treatment (5). With these sludges, greater depths are accompanied by higher settling velocities. While the effect of depth is particularly significant at high solids concentrations, there is no abrupt change to compression condition. Rather, an element of compression exists even at dilute concentrations.

In the preceding section and in the illustrative problem, the customary consideration

of the required volume or depth of the thickener as described by Roberts (11) was absent. This is because the settling velocities used were taken as those which actually occur in the thickener. That is, some "effective" depth in the thickener was assumed and this depth was used when the laboratory settling data were collected. In this way the determination of thickener area and depth are interrelated. Should it be desired to consider alternate effective depths, alternate flux curves corresponding to different initial depths could be evaluated.

It is, therefore, necessary to conduct laboratory settling tests at initial depths which give compression conditions comparable to the effective compression the corresponding concentration layer would experience in a full-scale thickener. Unfortunately the "effective" depth of a particular concentration layer in a full-scale thickener cannot be determined directly. This is because the weight of the overlying, more dilute solids, transmitted downward, influences the "effective" depth of a particular concentration in a continuous thickener as does the weight and structural rigidity of the more concentrated sludge below. Fortunately, sludge depth, unlike thickener area, is an operational variable. If settling tests for determination of required thickener area are conducted at depths conservatively representative of probable average field conditions, some flexibility will remain in operation of the thickener. Rarely are thickeners operated under steady conditions. Indeed, the most rational approach to establishing the depth of a thickener may be to consider the volume required to store the excess sludge which accumulates when the feed rate exceeds the solids-handling capacity of the thickener.

Mixing is another factor which influences settling as observed in laboratory batch tests. Traditionally, it has been thought that slow-speed stirring is necessary in laboratory settling tests to duplicate the mixing conditions caused by rake action and turbulence in full-scale thickeners. Recent work by Vesilind (18) suggests that stirring serves to eliminate the artificial conditions imposed by small laboratory settling columns rather than to duplicate the stirring conditions in full-scale thickeners. Vesilind tried a variety of stirrer configurations and speeds in settling columns of various diameters. He found that slow-speed stirring dramatically hastened settling in small columns, but that the beneficial effect diminished with increasing column diameter, and that no difference between stirred and unstirred conditions could be detected in 36-in diameter columns. Vesilind's conclusion was that while slow-speed stirring is essential in laboratory settling tests, its purpose is not to simulate the pickets or rakes in full-scale thickeners, but to cause the same agglomeration of solids to occur in small containers that occurs naturally in large containers.

While the ordinary effect of slow stirring of sludges from waste treatment is to increase settling rates, Scott has reported that slow stirring reduces the subsidence rate of flocculated pyrophylite (13), calcium carbonate (14), and flocculated silica (15). Scott has interpreted the cause of this decrease to be the disruption of channels which form between sludge particles to permit more rapid egress of displaced water. He considered the channels to be a laboratory anomaly. Their presence in field-scale thickeners is prevented by rake and slurry movement.

Thus, although laboratory batch-settling tests are easy to run, their interpretation is difficult. Observed results depend on the conditions under which the tests are conducted and on the properties of the sludge tested. The difficulties in understanding laboratory sedimentation and in applying results to the design or control of thickeners have led to several recent studies of the fundamental behavior of thickening suspensions. The rheological behavior of activated sludge has been investigated (4) and related to the thickening characteristics of the suspension (3). Scott (13) and (14) has described three settling regimes for concentrated suspensions. At dilute concentrations, particles settle as in-

dividual units as in an "ideal" slurry. At high concentrations, subsidence is brought about by mechanical compression. At intermediate concentrations, channel formation gives rise to abnormally high settling velocities. The formation of channels within settling slurries has also been studied by Dell and Kaynar (2). Scott (12) has described a change from interaggregate to intra-aggregate flow during thickening, and Javaheri and Dick have computed the changes in size, number, and specific gravity of activated-sludge aggregates as thickening takes place.

To summarize, the major factors which affect laboratory data are diameter, depth, and stirring conditions. I have used column diameters of 3.5 in or more, depths of about 3 ft, and mixer-tip speeds of slightly less than 10 in/min for work with activated sludge. However, it is not advisable to establish standard test conditions because of differences in the physical nature of various types of sludges.

FLOTATION

Recent developments in flotation thickening have largely been in application of the process. Little has been done to advance basic understanding of the process or to develop rational methods for design and control of this method of sludge thickening.

Because of the difficulty in thickening activated sludge to high concentrations by gravity thickening, most recent applications of dissolved air-pressure flotation in waste treatment have been for concentrating activated sludge. Katz and Geinopolos (9) and Jones (8) have reviewed the performance of activated-sludge flotation equipment at twenty plants. Float solids averaged 4.6 percent at plants which do not condition with polymers, while solids capture averaged slightly less than 90 percent. Plants which used polymers captured an average of 98.6 percent of the activated-sludge solids and produced an average thickened sludge with 5.8 percent solids.

At present, design and control of flotation processes is an empirical art involving correlations of air to solids ratios and rise rates with float solids concentrations and clarification efficiencies. Other than the difference in the direction of separation, flotation differs from gravity thickening only in that flotation systems include provisions for rendering the solids floatable. This introduces design and operational variables which are not involved in gravity thickening. While the basic utility of the solids flux curve (Figure 197) would seem to extend to flotation thickening, it has not been used in evaluating the effect of operational variables such as recycle ratio, feed concentration, pressure, polymer concentration, and float concentration. Procedures have been developed for conducting laboratory flotation tests (6), but the relationship of flotation characteristics in laboratory units to those in full-scale equipment has not been reported. It is likely that the limitations of laboratory flotation data are less severe than for laboratory settling data, because of the faster separation rates involved.

SUMMARY

Thickening is an important part of waste-treatment systems because it accomplishes major sludge volume reductions at a low cost. Thickening may be accomplished in gravity or flotation thickeners. Recent fundamental advances in thickening have related mostly to gravity thickening.

The theoretical thickening behavior of sludges is relatively well understood, and convenient techniques are available for using knowledge of basic suspension settling properties for thickener design and for rational control of thickener operation. Determination of the required area and volume for thickening are interrelated. It is proposed that area

determination should be based on settling characteristics of the suspension while volume determination normally should be based on the need for storing sludge during periods when the solids feed rate exceeds the capacity of the thickener for passing solids.

The major need in thickening technology at present is to learn more about the manner in which sludges subside in laboratory and full-scale thickeners so as to permit collection of settling data which give more accurate determination of design and operational requirements. It is thought, however, that thickening technology has advanced to the degree that sizing and operation of thickeners may be done on a rational basis.

REFERENCES

(1) Burd, R. S. *A Study of Sludge Handling and Disposal*. Federal Water Pollution Control Administration, Publication No. WP-20-4 (1968).

(2) Dell, C. C. and M. B. Kaynar. "Channelling in Flocculated Suspensions," *Filtration and Separation*, *5*, 323 (1968).

(3) Dick, R. I. "Thickening Characteristics of Activated Sludge," *Advances in Water Pollution Research*, Proceedings of Fourth International Conference on Water Pollution Research held in Prague, Czechoslovakia (September 1968).

(4) Dick, R. I. and B. B. Ewing, "The Rheology of Activated Sludge," *Journal, Water Pollution Control Federation*, *39*, 543 (1967).

(5) ———. "Evaluation of Activated Sludge Thickening Theories," *Journal, Sanitary Engineering Division, American Society of Civil Engineers*, *93* (SA4), 9 (1967).

(6) Eckenfelder, W. W., Jr. *Industrial Water Pollution Control* New York, N. Y.: McGraw-Hill, Inc. (1966).

(7) Javaheri, A. R., and R. I. Dick. "Aggregate Size Variations During Thickening of Activated Sludge," *Journal, Water Pollution Control Federation 41* (2) R 197 (1969).

(8) Jones, W. H. "Developments with Pressurized Flotation," Paper presented at 38th Annual Conference of the Water Pollution Control Federation, Atlantic City, New Jersey (1965).

(9) Katz, W. J., and A. Geinopolos. "Sludge Thickening by Dissolved-Air Flotation," *Journal, Water Pollution Control Federation*, *39*, 946 (1967).

(10) Kynch, G. J. "A Theory of Sedimentation," *Transactions, Faraday Society*, *48*, 166 (1952).

(11) Roberts, E. J. "Thickening: Art or Science?" *Mining Engineering*, *1*, 61 (1949).

(12) Scott, K. J. "Mathematical Models of Mechanisms of Thickening," *Industrial and Engineering Chemistry Fundamentals*, *5*, 109 (1966).

(13) ———. "Theory of Thickening: Factors Affecting Settling Rate of Solids in Flocculated Pulps," *Transactions, Institution of Mining and Metallurgy*, *77*, C85 (1968).

(14) ———. "Thickening of Calcium Carbonate Slurries: Comparison of Data with Results for Rigid Spheres," *Industrial and Engineering Chemistry Fundamentals*, *7*, 484 (1968).

(15) ———. "Experimental Study of Continuous Thickening of a Flocculated Silica Slurry," *Industrial and Engineering Chemistry Fundamentals*, *7*, 582 (1968).

(16) Shannon, P. T., R. D. Dehaas, E. P. Stroupe, and E. M. Tory. "Batch and Continuous Thickening," *Industrial and Engineering Chemistry Fundamentals*, *3*, 250 (1964).

(17) Vesilind, P. A. "Discussion of 'Evaluation of Activated Sludge Thickening Theories' by R. I. Dick and B. B. Ewing," *Journal, Sanitary Engineering Division American Society of Civil Engineers*, *94* (SA-1), 185 (1968).

(18) ———. "*The Influence of Stirring in the Thickening of Biological Sludge*," Ph.D. Thesis, University of North Carolina, Chapel Hill (1968).

APPENDIX VIII

ROLE OF ACTIVATED SLUDGE FINAL SETTLING TANKS

by

Richard I. Dick

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ROLE OF ACTIVATED SLUDGE FINAL SETTLING TANKS

By Richard I. Dick,[1] M. ASCE

INTRODUCTION

The characteristic feature of the activated sludge process is that biological solids are separated from treated effluent for recycle back into the process. Efficient performance requires that the separation be done effectively because the solids are needed to sustain the process and because solids which escape separation impair the quality of the effluent. In addition, it is important that the solids be consolidated into a concentrated suspension before being recycled because the performance of the overall process depends on the number of active microorganisms which can be crowded into each unit of aeration tank volume.

Unfortunately, the light, flocculent, biological solids formed in the activated sludge process usually do not settle and compact well. Hence, the effluent quality which can be achieved by activated sludge treatment as well as the size and cost of the required facilities often is controlled by the settling characteristics of the sludge.

Final settling tanks thus must be designed to accomplish high degrees of recovery and consolidation of activated sludge solids. Regrettably, attempts to design activated sludge waste treatment plants on a rational basis normally have been limited to consideration of biological aspects of the process. Little attention has been given to rational analysis of the solids separation phase.

In this paper, the need for more thorough consideration of the final settling tank in design of activated sludge plants is noted, and the fundamental bases for rational design of the tank are described. An example is presented to

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show how failure to consider the solids loading on the final settling tank can lead to unsatisfactory performance of the entire activated sludge process.

ROLE OF FINAL SETTLING TANK

Like any settling basin, the final settling tank in the activated sludge process has two functions: (1) The production of an effluent which is relatively free of settleable solids; and (2) the production of an underflow which contains, in high concentration, the solids which have been settled in the tank. Both functions, clarification and thickening, must be considered in design if the basin is to satisfactorily accomplish both of its tasks.

The importance of the clarification function of final settling tanks is illustrated in Fig. 1. As shown by the figure, the total BOD of the effluent from an activated sludge treatment plant is the dissolved BOD plus the BOD of the suspended solids. While the BOD equivalent of activated sludge solids depends on the treatment plant loading (8)[2] and other factors, each milligram

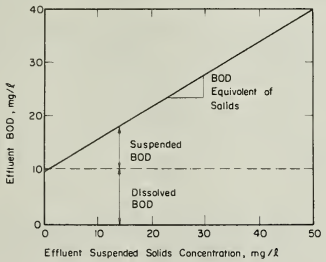

FIG. 1.—EFFECT OF CLARIFICATION ON QUALITY OF EFFLUENT FROM ACTIVATED SLUDGE PLANT

of solids lost over the weir of the final settling tank commonly increases the effluent BOD by about 0.6 mg. Thus, if, as in Fig. 1, the dissolved effluent BOD is 10 mg per l, then with an effluent suspended solids concentration of about 20 mg per l, over half of the total BOD leaving an activated sludge plant is in the form of solids which were not removed in the sedimentation process. The further deterioration of effluent quality which can be caused by still less effective solids removal is apparent from Fig. 1.

The consequence of inadequate performance of the other function of final settling tanks, thickening, is more complex. Improper design for the thickening function of final tanks can lead to direct deterioration of effluent quality by loss of suspended solids just as improper design of the clarification function can. In this case solids are lost because the basin lacks adequate capacity for conveying solids to the bottom of the tank. The mechanism responsible for loss of solids due to inadequate attention to thickening is described in

[2] Numerals in parentheses refer to corresponding items in the Appendix I.—References.

more detail in a later section. In addition, improper thickening in the final settling tank can lead to disruption of the treatment process by altering conditions in the biological phase of the process because of inefficient return of solids. This effect can be illustrated by considering that the basic design parameter in the activated sludge process is the number of pounds of BOD applied per pound of activated sludge solids under air, i.e., the organic loading intensity. The amount of BOD applied is established by the characteristics of the waste and the waste flow. The mass of activated sludge to which this load is applied depends on the volume of the aeration tank and the mixed liquor suspended solids concentration, (MLSS). With an existing plant, the aeration tank volume is fixed and the MLSS depends on the degree of sludge consolidation which is accomplished in the final settling tank. Fig. 2 illustrates this dependence of the MLSS on the underflow concentration from the final settling

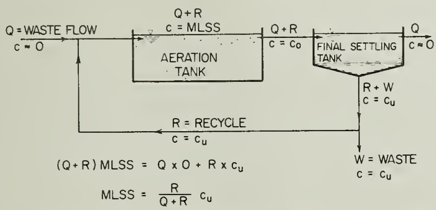

FIG. 2.—DEPENDENCE OF MIXED LIQUOR SUSPENDED SOLIDS CONCENTRATION ON FINAL SETTLING TANK UNDERFLOW CONCENTRATION

tank, c_u. If the suspended solids content of the waste flow and synthesis of solids in the aeration tank are ignored then

$$\text{MLSS} = \frac{R}{Q + R} c_u \quad \text{(1)}$$

in which Q and R are the waste flow rate and the rate of recycle. As illustrated by Eq. 1, failure to design the final settling tank to give the desired underflow concentration will lead to a decrease in the MLSS and hence to an increase in the organic loading intensity. The increase in organic loading intensity may adversely alter the flocculating and settling characteristics of the sludge (7) and make it even more difficult to achieve the desired underflow concentration. Hence, the problem becomes compounded. In this case, what may appear to be a problem related to the biological aspects of the activated sludge process actually stems from inadequate design of the solids separation phase of the process.

From the preceding analysis it may be seen that the size and cost of the aeration tank can be reduced by adequate design of the final settling tank. That is, if the final tank can be designed to assure that solids will be returned in sufficiently high concentration, the required amount of solids under aeration can be contained in a smaller aeration tank. Also, since the cost of virtually all methods of waste sludge treatment and disposal depends on the concentration of solids in the sludge, proper thickening in the final settling

tank can reduce the cost of dealing with the waste sludge which is identified as W in Fig. 2.

DESIGN OF FINAL SETTLING TANKS

To assure that a final settling tank satisfactorily accomplishes both of its functions, both clarification and thickening must be considered in design. If the size of the tank required to give the desired degree of clarification exceeds the size required to give the desired degree of thickening, then the clarification function governs sizing of the final settling tank. Conversely, if the thickening requirement is greater, thickening governs. Conventional design procedures have considered only the clarification function, and the requirements for thickening are normally overlooked. Because the concepts relating to design requirements for the clarification function are well established they will be given only brief attention here. More attention will be given to the less familair concepts relating to design for the thickening function.

For proper clarification, sufficient surface area must be provided in the final settling tank so that the hydraulic loading per unit area does not exceed the settling velocity of the slowest settling material which is to be completely removed. The settling velocity of interest is often taken as the zone settling velocity of the activated sludge at the MLSS concentration (5), although it is likely that consideration of the subsidence of individual floc particles found in the upper regions of final settling tanks would impose more limiting conditions. If it is desired to take advantage of the flocculant nature of the activated sludge solids to accomplish removal of the dilute solids in the upper part of final settling tanks, then sufficient volume must be provided in the clarification section of the tank to permit particle collisions to occur (4).

To assure that final settling tanks satisfactorily accomplish their thickening function, sufficient area must be provided so that solids are applied at a rate which is not in excess of the rate at which solids are able to reach the bottom of the tank. The biological solids are transported to the bottom of the final settling tank by two mechanisms. One mechanism is their subsidence under the influence of gravity, and the other is the bulk downward transport due to sludge withdrawal from the bottom of the settling tank. The total rate at which solids of concentration c_i pass downward in the final settling tank is

$$G = c_i v_i + c_i u \qquad (2)$$

in which G is the solids flux, commonly in pounds per square foot per day, v_i is the settling velocity of the activated sludge solids at concentration c_i, and u is the average downward velocity caused by removal of sludge from the bottom of the settling tank at concentration c_u.

The amount of solids transported by gravity subsidence, $c_i v_i$, depends on the settling characteristics of the sludge, whereas the amount transported by sludge withdrawal, $c_i u$, is a variable controlled within limits by the operator of the activated sludge process. The operator can vary the value of u by varying the rate of removal of thickened sludge from the bottom of the tank. Assuming essentially complete solids capture, the total mass of solids, M, to be thickened in a final settling tank per unit time is

$$M = Q_o c_o = Q_u c_u \qquad (3)$$

in which Q_u and c_u are the flow rate and solids concentration of sludge removed from the tank; and Q_o and c_o are the influent flow rate (including recycle) and solids concentration. The average bulk downward velocity due to solids removal, u, is then

$$u = \frac{Q_u}{A} = \frac{M}{c_u A} \qquad (4)$$

Thus, for a fixed solids loading, M, on a final settling tank with area, A, the rate of bulk downward movement, u, is related inversely to the concentration at which sludge is withdrawn from the tank. The goal of proper solids control in the activated sludge process might be thought of as getting the solids to the bottom of the final settling tank by maximizing the $c_i v_i$ term in Eq. 2 through improvement of the settling characteristics of the sludge solids and by minimizing the $c_i u$ term by removing underflow at the highest possible concentration.

In the final settling tank, opportunity is afforded for activated sludge to exist in all concentrations from that of the mixed liquor to that of the underflow. In fact, if dilution with previously clarified effluent occurs at the inlet, concentrations below the MLSS concentration will exist. Hence, c_i in Eq. 2 can assume all values from less than c_o to c_u. With a particular activated sludge, the rate of gravity subsidence, v_i, depends primarily on the solids concentration, c_i. Characteristically, v_i varies with c_i in such a fashion that the flux rate, G, in Eq. 2 passes through a minimum for some limiting concentration of activated sludge solids. This minimum value of possible solids flux is the limiting solids handling capacity, G_L, of the suspension and is the basis for determining the area required in a final settling tank to accomplish the desired degree of thickening. This required area is

$$A = \frac{M}{G_L} = \frac{Q_o c_o}{G_L} \qquad (5)$$

For example, if a final settling tank is to receive 60,000 lb per day of solids and the limiting solids handling capacity, G_L, as given by the minimum value of G for concentrations expected to occur within the settling tank, is 20 lb per sq ft per day, then 3,000 sq ft of final settling tank area must be provided to assure that all solids will be transported to the bottom of the tank.

It ordinarily has been considered that in addition to the area required for thickening, a certain volume, or depth, also must be provided. The volume requirement commonly has been felt to be associated with the need for time to accomplish compression of the sludge solids. Analysis of the volume requirement for thickening has not been developed on a rational basis, but several empirical methods have been proposed (1,6). Fortunately, volume is not considered to be the primary factor controlling thickening (11). Eq. 2 is a general equation which applies to all concentrations of sludge. There would seem to be no need for a separate set of concepts to deal with the high concentrations associated with compression of sludges as long as all concentrations up to the underflow concentration are considered in selecting the limiting solids flux. The volume required for thickening is, then, that which provides sufficient depth to assure that settling velocities which occur in the final settling tank are the same as those used in Eq. 2 for determining the required area. In addition, it is necessary to provide sufficient volume to assure that thickened sludge will be transported to the point of sludge with-

drawal without being mixed with more dilute solids and to allow for accumulation of solids during any period when the rate at which solids enter the thickener exceeds the rate of removal of thickened solids.

It is commonly held that the volume of sludge retained in the final settling tank must be minimized to assure quick return of the sludge to avoid anaerobiosis and accompanying deterioration of sludge quality. While this seems reasonable, few data are available to support the merit of the practice. Indeed, Whurmann (16) reported that the properties of activated sludge were not influenced by exposure to long periods of anaerobiosis, and workers at the British Water Pollution Research Laboratory (15) have shown that retention of activated sludge solids under anaerobic conditions for periods of 24 hr did not adversely influence the sludge. Indeed, in addition to the possible merits of retention of sludge in final settling tanks for thickening, it has been proposed that holding sludge under oxygen deficient conditions can be used advantageously to control growth of unwanted organisms (9). Possible adverse effects of long term retention of activated sludge solids are flotation due to denitrification (10) and release of phosphates previously removed by the activated sludge solids (12).

ILLUSTRATION

The role of thickening in the activated sludge process and concepts regarding the design of settling tanks to accomplish their thickening functions can be best illustrated by example. The data used in this illustration are for an actual activated sludge from a municipal contact stabilization plant with an average organic loading of about 0.5 lb BOD per day per lb sludge solids. Activated sludge thickening is a problem at the plant; often sludge can not be withdrawn from the final tank at concentrations greater than 2,500 mg per l to 3,500 mg per l. This sludge was purposely selected for use in the illustration to emphasize that thickening concepts are involved even when solids concentrations are much less than 1% by weight. Fig. 3 shows the settling characteristics of the sludge solids as established by laboratory settling tests. Procedures for collection of these data are considered briefly in a later section.

For purposes of illustration, presume that a 1-MGD plant has been designed, and that the final settling tank was conventionally sized on the basis of an overflow rate of 800 gpd per sq ft, as commonly might be done. Thus the final tank would have a surface area of 1,250 sq ft and be 40 ft in diam. Presume further that the waste entering the activated sludge process has a BOD of 200 mg per l, that the biological portion of the design was based on an organic loading intensity of 0.5 lb BOD per day per lb MLSS, and that it was conservatively estimated that 2,000 mg per l of mixed liquor suspended solids would be maintained. The aeration tank volume hence would have to be 0.2 mg.

The assumed final settling tank design is typical of conventional practice with attention being given to only the clarification function of the basin. Consider now the ability of the basin designed in this fashion to carry out its thickening function. From inspection of Fig. 3, it is tentatively concluded that, for this sludge, 6,000 mg per l is a reasonable goal for the suspended solids concentration of the return sludge. Using this value for c_u, the required recycle rate, R, from Eq. 1 is 50%, or 0.5 MGD, if 2,000 mg per l MLSS are to

be maintained. The total solids loading on the final tank produced by the flow of 1.5 MGD at 2,000 mg per l is, from Eq. 3, 25,000 lb per day or 20 lb per sq ft per day. Ignoring the waste sludge flow, W, the average bulk downward

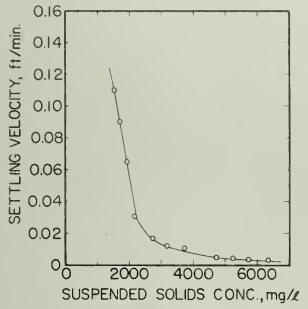

FIG. 3.—SETTLING CHARACTERISTICS OF ACTIVATED SLUDGE CONSIDERED IN ILLUSTRATIVE PROBLEM

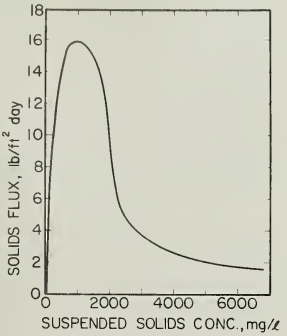

FIG. 4.—SOLIDS TRANSPORT DUE TO SEDIMENTATION

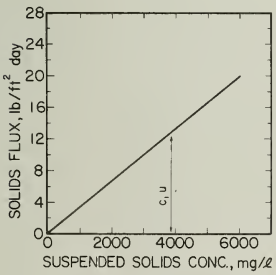

FIG. 5.—SOLIDS TRANSPORT DUE TO SLUDGE WITHDRAWAL WITH 50% RECYCLE

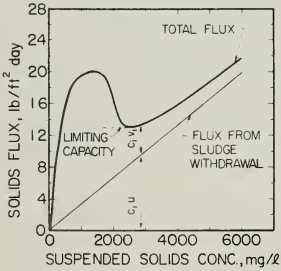

FIG. 6.—TOTAL POSSIBLE SOLIDS TRANSPORT WITH 50% RECYCLE

velocity, u, produced by removal of 0.5 MGD from the bottom of the tank, from Eq. 4, is 0.037 ft per min.

Will all of the solids be able to reach the bottom of the tank? The possible solids transport for each concentration of the activated sludge due to gravity

subsidence alone is shown in Fig. 4. The curve represents the product of the settling velocity, v_i, from Fig. 3 and the associated concentration, c_i. The additional solids flux, $c_i u$, produced by the 0.037 ft per min bulk downward velocity is shown in Fig. 5. Fig. 6 shows the total possible solids flux for various suspended solids concentrations with the particular activated sludge and operating conditions described. The upper curve in Fig. 6 represents the sum of the curves in Figs. 4 and 5 as given by Eq. 2. It is seen that the solids handling capacity of this activated sludge under these operating conditions passes through a minimum limiting value of about 13 lb per sq ft per day at a suspended solids concentration of about 2,500 mg per l. The lower solids handling capacities on the rising portion of the curve at concentrations below about 400 mg per l are not of concern unless all of the solids are diluted with clarified effluent to a concentration below this value at the inlet of the tank. The shape of the curve in Fig. 6 is typical for activated sludge and other suspensions. The magnitude of the limiting solids flux and of the concentration corresponding to the limiting value change depending on the nature of the suspension and the operating conditions of the settling basin.

It is apparent that this activated sludge process is not going to perform as planned. To sustain the 2,000 mg per l MLSS concentration with a recycle rate of 50%, 20 lb per sq ft per day of activated sludge solids must be transmitted to the bottom of the settling basin. However, it is not physically possible for more than 13 lb per sq ft per day of the solids to pass through a layer with a concentration of 2,500 mg per l. Because in passing from the MLSS concentration to the underflow concentration solids must pass through a concentration of 2,500 mg per l, this concentration becomes a bottleneck limiting the performance of the thickening portion of the final settling tank, and no more than 13 lb per sq ft of tank area will reach the bottom.

If solids are applied to a rate greater than 13 lb per sq ft per day they will accumulate above the 2,500 mg per l layer. If the solids loading is sustained at a level greater than 13 lb per sq ft per day for a long period of time, the excess solids will propogate upward and be lost over the effluent weir. The total mass of solids, M, which can pass through the 1,250 sq ft tank is 16,250 lb per day, and from Eq. 3, the underflow concentration with the 0.5 MGD recycle rate will be 3900 mg per l, not 6,000 mg per l as planned. From Eq. 1 it is seen that the MLSS concentration can be maintained at only 1,300 mg per l and, hence, the organic loading intensity for the process will be increased to 0.77 lb BOD per day per lb sludge solids. This increase of more than 50% in the intended loading could lead to further deterioration of the settling characteristics of the sludge solids.

While alternate operating conditions are possible, none can produce the desired operating condition with 2,000 mg per l MLSS and a 50% recycle rate. For example, the solids flux due to bulk downward transport could be increased by increasing the recycle rate. Fig. 7 shows the solids handling capacity of the activated sludge with a 70% recycle rate with a resulting underflow concentration of 3,500 mg per l (Eq. 3). It is seen that the limiting solids handling capacity is increased to 16.5 lb per sq ft per day because of the greater bulk downward velocity; however, the MLSS concentration will be only 1,450 mg per l, the organic loading intensity will still be greater than planned (0.69 lb BOD per day per lb solids), and the actual retention time in the aeration tank will be reduced appreciably. The possible change in the settling characteristics of the sludge solids brought about by different operating

conditions has not been considered in estimating the alternate mode of operation.

For this plant, requirements for the thickening function should have governed sizing of the final clarifier. The tank should have been sized so that the 25,000 lb per day of solids could have been transmitted to the bottom. The example illustrates that when final clarifiers for an activated sludge process are designed without consideration for their thickening function, conditions may be created which make proper performance of the process impossible. Symptoms of improper design for the thickening function are the occasional excessive loss of solids over the final settling tank weir and the inability to withdraw sludge from the final settling tank in high enough concentration to maintain the desired mixed liquor suspended solids concentration in the aeration tank. It will be recognized that the symptoms are common in the operation of the activated sludge process. However, they are not commonly thought of as being caused by the limited capacity of the activated sludge suspension for transmitting solids to the bottom of the final clarifier.

ALTERNATE METHODS OF ANALYSIS

While the flux plots for a continuous thickener (Figs. 6 and 7) were useful in the preceding analysis of a final settling tank because they showed the rel-

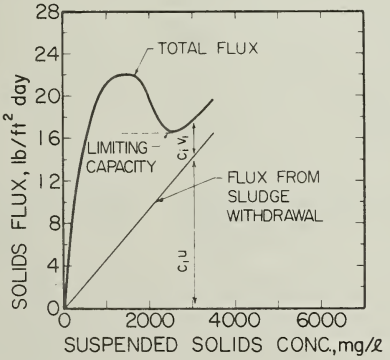

FIG. 7.—TOTAL POSSIBLE SOLIDS TRANSPORT WITH 70% RECYCLE

ative contributions of gravity subsidence and bulk transport, more convenient means of analysis are available. One method involves use of the approach described over 50 yr ago by Coe and Clevenger (2), and the other is use of batch flux plots as described by Yoshioka, et al. (17) and others. These methods are described in the paragraphs which follow.

The solids loading on a final settling tank, M, is equivalent to the actual

solids flux times the area of the basin or GA. Hence, from Eq. 4

$$u = \frac{G}{c_u} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Substituting this value for u in the basic equation for solids flux in a settling basin (Eq. 2) gives

$$G = \frac{v_i}{\frac{1}{c_i} - \frac{1}{c_u}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Eq. 7 is the same as the expression developed in a different manner by Coe and Clevenger. The required size of a thickener can be determined from Eq. 7 by substituting various values of c_i and v_i to determine the limiting solids handling capacity for alternative values of the underflow concentration, c_u. Fig. 8 shows plots of Eq. 7 for the data used in the illustrative problem when

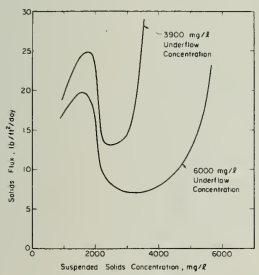

FIG. 8.—USE OF COE AND CLEVENGER METHOD (2) FOR IDENTIFYING LIMITING SOLIDS HANDLING CAPACITY

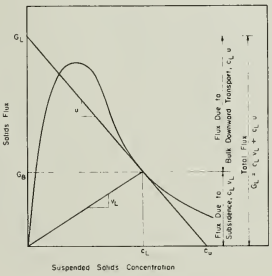
Solids Flux
Flux Due to Bulk Downward Transport, $c_L u$
Flux Due to Subsidence, $c_L v_L$
Total Flux
$G_L = c_L v_L + c_L u$
Suspended Solids Concentration

FIG. 9.—BATCH FLUX PLOT METHOD OF ANALYZING THICKENING PERFORMANCE OF FINAL SETTLING TANK

return sludge is removed at 6,000 mg per l and 3,900 mg per l. It is seen that if sludge were removed at 6,000 mg per l, capacity of the tank would be limited to 7 lb per sq ft per day. By adjusting the underflow rate to 50% recycle to give a thickened sludge concentration of 3,900 mg per l, the capacity is increased to 13 lb per sq ft per day. This value agrees with the result obtained by use of the continuous thickener flux plot in the preceding illustrative problem.

Because G in Eq. 6 was taken as the actual flux through the settling basin, Eq. 7 is valid only for the concentrations of sludge which exist in the settling tank. That is, the plot of G for c_u = 3,900 mg per l in Fig. 8 does not coincide with the upper curve in Fig. 6. Eq. 7 and the curves in Fig. 8 are valid at the concentration which limits the solids handling capacity of the thickener and hence can be used for sizing the area in a final settling tank required for thickening. The equation is not valid for other concentrations, however. This

shortcoming of the Coe and Clevenger approach limits its usefulness in analyzing the performance of an existing thickener.

Another means of analysis of design or operation of a thickener is much more convenient. This method involves use of a batch flux curve such as shown in Fig. 4. From Eq. 6, the slope of a line connecting a flux, G, on the ordinate axis of a batch flux plot with the corresponding underflow concentration, c_u, is the bulk downward velocity, u. Hence, as illustrated by Fig. 9 in conjunction with Eq. 2, the design or operation of a final settling tank can be evaluated directly from a batch flux plot. The solids flux represented by the distance from the origin to G_B, $c_L v_L$, is the solids transport due to subsidence. The additional flux, $c_L u$, due to the bulk downward transport of the

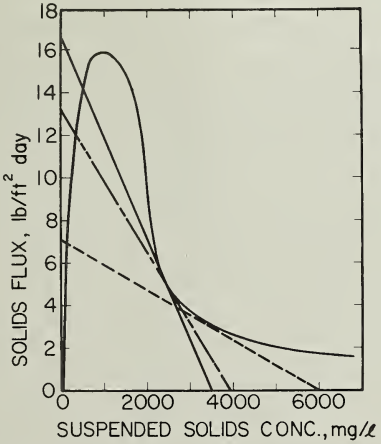

FIG. 10.—USE OF BATCH FLUX PLOT TO READILY DETERMINE ALTERNATE OPERATING CONDITIONS CONSIDERED IN ILLUSTRATIVE PROBLEM

final settling tank contents when sludge is removed at concentration c_u is represented by the distance between G_L and G_B in Fig. 9.

The convenience of the batch flux curve method is illustrated in Fig. 10 where the three alternate operating conditions previously calculated are obtained simply by striking three tangents, operating lines, to the flux curve. As before, it is seen that when thickened activated sludge is withdrawn at 3,900 mg per l, capacity of the thickener is limited to 13 lb per sq ft per day by the ability of the sludge at 2,500 mg per l to transmit solids under the operating conditions. Similarly, the limiting capacity when sludge is withdrawn at 3,500 mg per l is seen to be 16.5 lb per sq ft per day in agreement

with Fig. 7, and 7 lb per sq ft per day when sludge is withdrawn at 6,000 mg per l as previously shown in Fig. 8.

The three methods for analyzing the thickening function of final settling tanks, the component method illustrated by Fig. 6, the Coe and Clevenger method shown in Fig. 8, and the batch flux plot method demonstrated in Fig. 10, do not differ fundamentally, and all give the same results. They have been presented in order of increasing convenience for routine use and in order of increasing complexity for acquiring insight into the concepts involved in design of the thickening function of settling basins. These methods, especially the batch flux plot technique, are equally useful in analysis of performance of an existing final tank. The effect of operational changes can be anticipated by drawing various operating lines on a curve such as Fig. 10.

COLLECTION AND ANALYSIS OF SETTLING DATA

The data needed for analysis of design or operation of final settling tanks are those describing the relationship between suspended solids concentration, c_i, and settling velocity, v_i. From these data a reasonable return sludge suspended solids concentration and the limiting solids handling capacity can be estimated. The required data are obtained by multiple batch settling tests, using various initial concentrations of the activated sludge. The slope of the straight line portion of the batch settling curve is taken as the settling velocity of the sludge at its initial concentration.

While it is not the purpose of this paper to consider techniques for gathering meaningful sedimentation data, it would be remiss not to mention common pitfalls in collecting the data. The turbulence level created in dispersing the solids at the beginning of the settling test can influence results because nonhomogeneous conditions can be created while the turbulence subsides (3). Observed settling velocities are influenced by the initial depth of sludge in the batch settling column (3). Settling tests must be conducted with sludge depths representative of the effective depth which is expected to occur in the final tank. The presence of the wall in laboratory settling columns can have a profound effect on settling characteristics. With a given sludge, the wall effect can be either to retard or to hasten subsidence, depending on the solids concentration (14). Slow mixing is extremely important in laboratory settling tests. Indications are that the role of mixing is to minimize the wall effect and not primarily, as has been presumed, to duplicate the rake action in full scale settling basins (13).

The state-of-the-art is not such that precise conditions for laboratory settling tests which will give results representative of field performance can be specified. The data used in the previous example were obtained from laboratory settling columns 3.5 in. in diam with initial sludge depths of 3.5 ft with a stirring rate of 1 rpm. Initial distribution of the solids in the settling column was obtained by pumping the sludge into the column at a controlled rate.

SUMMARY

Conventional procedures for design of final settling tanks in the activated sludge process consider only the clarification function of the tanks. Failure

to consider the thickening function of final settling tanks can lead to unnecessarily high capital costs, operational difficulties, and impairment to effluent quality.

Design for the thickening function of final settling tanks is based on the limiting solids handling capacity of the sludge. If a final settling tank is designed without regard for the limited capacity of the suspension for transmitting solids, a severe restriction may be imposed on the rate at which suspended solids can be passed through the settling basin. The result is a reduction in the amount of suspended solids which can be maintained in the aeration tank, and possibly a loss of suspended solids over the effluent weir. Because the solids handling capacity of a suspension is determined both by the settling characteristics of the sludge and by the way the final settling tank is operated, the capacity of an existing tank for transmitting solids can be increased by increasing the rate of sludge removal. However, this operational change reduces the suspended solids concentration in the sludge withdrawn from the tank.

Three techniques for analyzing the thickening performance of a final settling tank for design or operational purposes have been illustrated. The batch solids flux plot is the most convenient of the methods.

ACKNOWLEDGMENTS

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APPENDIX I.—REFERENCES

1. Behn, V. C., and Liebman, J. C., "Analysis of Thickener Operation," *Journal of the Sanitary Engineering Division*, ASCE, Vol. 89, No. SA3, Proc. Paper 3535, June, 1963, pp. 1–15.
2. Coe, H. S., and Clevenger, G. H., "Methods for Determining the Capacities of Slime Settling Tanks," *Transactions*, American Institute of Mining Engineers, Vol. 55, 1916, pp. 356–384.
3. Dick, R. I., and Ewing, B. B., "Evaluation of Activated Sludge Thickening Theories," *Journal of the Sanitary Engineering Division*, ASCE, Vol. 93, No. SA4, Proc. Paper 5367, August, 1967, pp. 9–29.
4. Dick, R. I., discussion of "Settling of Activated Sludge in Horizontal Tanks," by C. N. H. Fisherstrom, E. Isgard, and I. Larsen, *Journal of the Sanitary Engineering Division*, ASCE, Vol. 93, No. SA6, Proc. Paper 5623, December, 1967, pp. 271–273.
5. Eckenfelder, W. W., Jr., and Melbinger, N., "Settling and Compaction Characteristics of Biological Sludges," *Journal Water Pollution Control Federation*, Vol. 29, No. 10, Oct., 1957, pp. 1114–1122.
6. Edde, H. J., and Eckenfelder, W. W., Jr., "Theoretical Concepts of Gravity Sludge Thickening; Scaling-Up Laboratory Units to Prototype Design," *Journal Water Pollution Control Federation*, Vol. 40, No. 8, Aug., 1968, pp. 1486–1498.
7. Ford, D. L., and Eckenfelder, W. W., Jr., "Effect of Process Variables on Sludge Floc Formation and Settling Characteristics," *Journal Water Pollution Control Federation*, Vol. 39, No. 11, Nov., 1967, pp. 1850–1859.
8. McCarty, P. L., and Broderson, C. F., "Theory of Extended Aeration Activated Sludge," *Jour-*

nal Water Pollution Control Federation, Vol. 34, No. 11, Nov., 1962, pp. 1095–1103.
9. Okun, D. A., discussion of "Effect of Oxygen Tension in Biochemical Reactions in Sewage Purification Plants," by K. Wuhrmann, *Advances in Biological Waste Treatment*, W. W. Eckenfelder, Jr., and J. McCabe, eds., Pergamon Press, New York, 1963, pp. 38–39.
10. Sawyer, C. N., and Bradney, L., "Rising of Activated Sludge in Final Settling Tanks," *Sewage Works Journal*, Vol. 17, No. 6, Nov., 1945, pp. 1191–1209.
11. Shannon, P. T., and Tory, E. M., "The Analysis of Continuous Thickening," *Society for Mining Engineers of* AIME *Transactions*, Vol. 235, No. 12, Dec., 1966, pp. 375–382.
12. Shapiro, J., Levin, G. V., and Humberto, Z. G., "Anoxically Induced Release of Phosphate in Waste Water Treatment," *Journal Water Pollution Control Federation*, Vol. 39, No. 11, Nov., 1967, pp. 1810–1818.
13. Vesilind, P. A., "The Influence of Stirring in the Thickening of Biological Sludge," thesis presented to the University of North Carolina at Chapel Hill, North Carolina, in 1968 in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
14. Vesilind, P. A., discussion of "Evaluation of Activated Sludge Thickening Theories," by R. I. Dick and B. B. Ewing, *Journal of the Sanitary Engineering Division*, ASCE, Vol. 94, No. SA1, Proc. Paper 5773, February, 1968, pp. 185–190.
15. Water Pollution Research Board, *Water Pollution Research 1962*, Department of Scientific and Industrial Research, London, England, 1962.
16. Wuhrmann, K., "Effect of Oxygen Tension in Biochemical Reactions in Sewage Purification Plants," *Advances in Biological Waste Treatment*, W. W. Eckenfelder, Jr., and J. McCabe, eds., Pergamon Press, New York, 1963, pp. 27–38.
17. Yoshioka, N., et al., "Continuous Thickening of Homogeneous Flocculated Slurries, *Chemical Engineering*, Tokyo, Vol. 21, No. 2, 1957, pp. 66–74.

APPENDIX II.—NOTATION

The following symbols are used in this paper:

A = area of settling basin, L^2;
c = concentration of suspended solids, M/L^3;
c_i = suspended solids concentration in layer i, M/L^3;
c_L = suspended solids concentration of layer with minimum capacity for transmitting solids, M/L^3;
c_o = suspended solids concentration of flow entering final settling tank, M/L^3;
c_u = underflow suspended solids concentration from final settling tank, M/L^3;
G = solids flux, $M/L^2/T$;
G_L = limiting solids handling capacity, $M/L^2/T$;
M = total suspended solids loading on final settling tank, M/T;
Q = rate of flow of waste entering activated sludge process, L^3/T;
Q_o = rate of flow of waste entering final settling tank, L^3/T;
Q_u = rate of sludge removal from settling basin, L^3/T;
R = rate of recycle of activated sludge, L^3/T;
u = average bulk downward velocity in settling tank caused by sludge removal, L/T;
v_i = settling velocity of sludge with suspended solids concentration c_i, L/T;
v_L = settling velocity of layer with limiting solids handling capacity, L/T; and
W = rate of flow of waste activated sludge, L^3/T.

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